

THE GREAT COURSES®

Science & Mathematics



Great Ideas of
Classical Physics

Taught by: Professor Steven Pollock,
University of Colorado at Boulder

Part 2

Course Guidebook



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Steven Pollock is associate professor of physics at the University of Colorado, Boulder. He did his undergraduate work at MIT, receiving a B.Sc. in physics in 1982. He holds a master's and a Ph.D. in physics from Stanford University, where he completed a thesis on "Electroweak Interactions in the Nuclear Domain" in 1987. He did postdoctoral research at NIKHEF (the National Institute for Nuclear and High Energy Physics) in Amsterdam from 1988–1990 and at the Institute for Nuclear Theory in Seattle from 1990–1992. He spent a year as senior researcher at NIKHEF in 1993 before moving to Boulder.

From 1993–2000, Professor Pollock's research work focused on the intersections of nuclear and particle physics, with special focus on parity violation, neutrino physics, and virtual strangeness content of ordinary matter. Around the time he received tenure at CU Boulder, Professor Pollock began shifting his attention to the newly developing discipline-based research field of physics education research. This field now represents his full-time physics research activities.

Professor Pollock was a teaching assistant and tutor for undergraduates throughout his years as both an undergraduate and graduate student. As a college professor, he has taught a wide variety of university courses at all levels, from introductory physics to advanced nuclear and particle physics, including quantum physics (both introductory and senior level) and mathematical physics, with intriguing recent forays into the physics of energy and the environment and the physics of sound and music.

Professor Pollock is the author of *Thinkwell's Physics I*, a CD-based introductory physics "next-generation" multimedia textbook. He became a Pew/Carnegie National Teaching Scholar in 2001 and is currently pursuing classroom research into replication and sustainability of reformed teaching techniques in (very) large lecture introductory courses. Professor Pollock received an Alfred P. Sloan Research Fellowship in 1994, the Boulder Faculty Assembly (CU campus-wide) Teaching Excellence Award in 1998, and the Marinus G. Smith Recognition Award in 2006. He has presented both nuclear physics research and his scholarship on teaching at numerous conferences, seminars, and colloquia. He is a member of the American Physical Society, the Forum on Education, and the American Association of Physics Teachers.

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Great Ideas of Classical Physics

Scope:

Physics is the science that tries to understand the deep principles underlying the world we live in. It's about understanding and describing nature. It's about *things*, as opposed to biological or even chemical *systems*. *How* do things move? *Why* do they move? How do they *work*? Physicists search for deep patterns, for the fundamental simplicity and unity of measurable phenomena. In this course, we will follow a theme-based, quasi-historical path, highlighting the central concepts, ideas, and discoveries of classical physics. *Classical* here refers to scientific work done up to the start of the 20th century, that is, essentially all physics before the quantum theory and relativity. It is the physics of everyday life, the physics of a deterministic "clockwork" universe, with enormous explanatory and predictive power! We will spend a little time getting to know the characters who played key roles, including Galileo, Newton, Faraday, Maxwell, and others, but the emphasis of the course is on sense-making: What have physicists learned about the world? What are the key underlying laws of nature? What are the primary organizing principles? How can we use these ideas and connect them to our personal experiences?

Physics is a broad field of study and can be approached from many angles. We begin with a venerable branch of physics known as *mechanics*, the study of forces, energy, and motion. The word *mechanics* might make one think of car engines, and in some ways, that's a good metaphor. Engines are complicated, but they are built out of simple and comprehensible parts, each of which serves a simple purpose. When put together, they create a familiar, useful, and understandable (by mechanics!) whole. But *mechanics* in physics is not about cars; it's the study of how just about anything moves and what makes objects behave as they do when acted on by forces. It's a study that will help us understand a vast and disparate array of phenomena, from Olympic high divers, to the display of sparks in a firework on the 4th of July, to the path of the Moon in the night sky, or the ceaseless bounce and jitter of atoms in a gas. We will focus on the central concepts: What do we know, and how do we know it? We'll ask where the ideas came from and how we might test them. And, of course, we'll ask what we can do with this knowledge. Classical mechanics is primarily the physics of Isaac Newton and a host of other brilliant characters who laid the groundwork for understanding the world that is still relevant 400 years after its beginnings. Our goal is to walk away with a sense of the order and coherence, the basic structure and principles of this foundation of physics.

Mechanics sits underneath the rest of physics a bit like the foundation of a great cathedral. The second half of the course will add the edifice, structure, and turrets. We will need to understand the ideas behind *electricity* and *magnetism*, forces that dominate our technological world and lead to understanding of the structure of all matter and light. This investigation leads naturally to *optics*,

which was unified with electricity and magnetism in a brilliant stroke in the mid-1800s. In this context, we will briefly consider *waves* and the myriad phenomena that become understandable, and intimately related to one another, once we grasp the basic ideas and consequences of vibrations. We will need to learn separately about *heat* and *thermodynamics*, a branch of classical physics that deals with everything from understanding car engines and power supplies to making a perfect cake. This course of study takes us right up to the start of the 20th century.

One final comment: Mathematics plays a special role in science, one very dear to physicists, but we will not (and need not) focus on math in this course. Although skipping the equations limits, to some extent, the depth to which we can learn physics, the concepts themselves are, by and large, sensible, intuitive, and comprehensible through metaphor, life experience, ordinary logic, and common sense. From time to time, however, we may follow brief mathematical detours to appreciate the power and beauty of more formal or symbolic reasoning!

Notes on Course Materials: Suggested readings and computer simulations are listed with each lecture, using the abbreviations noted below.

Essential Computer Simulations (“Sims”):

These are all available at <http://phet.colorado.edu> and should run on PC or Mac. (Some of the Java applications require a fairly current Mac OS.)

Essential Reading:

<i>Thinkwell</i>	Professor Pollock’s <i>Thinkwell Physics I</i> , www.thinkwell.com .
Hewitt	Paul G. Hewitt, <i>Conceptual Physics</i> , Addison Wesley, 2005.
Hobson	Art Hobson, <i>Physics: Concepts and Connections</i> , Prentice Hall, 2006.
March	Robert March, <i>Physics for Poets</i> , McGraw-Hill, 2002.

Recommended Reading:

Feynman	Feynman, Leighton, and Sands, <i>The Feynman Lectures on Physics</i> , Addison Wesley, 1963.
Cropper	William H. Cropper, <i>Great Physicists</i> , Oxford University Press, 2001.
Gleick	James Gleick, <i>Isaac Newton</i> , Vintage, 2003.
Lightman	Alan Lightman, <i>Great Ideas in Physics</i> , McGraw Hill, 2000.
Crease	Robert P. Crease, <i>The Prism and the Pendulum</i> , Random House, 2003.
Gonick	Larry Gonick and Art Huffman, <i>The Cartoon Guide to Physics</i> , Collins, 2005.

Lecture Thirteen

Further Developments—Static Electricity

Science is built up of facts, as a house is with stones. But a collection of facts is no more a science than a heap of stones is a house.

—Henri Poincare

Scope: For 200 years following the publication of the *Principia*, growing numbers of scientists followed the path laid out by Newton—a path paved from a philosophical, mathematical, theoretical, and experimental groundwork. The scope of “physics” expanded steadily and rapidly, and we can only touch on the many “great ideas” developed in this period: electricity, magnetism, waves, optics, and the grand unification of those ideas. Heat and temperature, chemistry, and the atomic worldview make up another path for us to follow. We will study some of these grand ideas in upcoming lectures—a few very briefly and some in more detail—to get a sense of the sweeping scale of accomplishments of classical physics. In this lecture, we begin our story of post-Newtonian classical physics with the “new” forces of static electricity and magnetism. We’ll look at static electricity as a classic example of a systematic investigation into a force of nature, but we’ll see that this “new” force still fits in tightly with the Newtonian framework.

Outline

- I. Let’s begin with a road map for the rest of the course.
 - A. In covering some new topics, we will always begin with Newton’s ideas about forces, momentum, and energy and conservation laws.
 - B. In the second half of the course, we will talk about the fundamental constituents of the world, particularly atoms and their motion. We’ll see that the motion of particles is connected to theories of electricity and magnetism, as well as theories of light and optics. We will also explore thermodynamics.
 - C. We will discover a new hero in this part of this course, James Clerk Maxwell (1831-1879), who is to electricity and magnetism what Newton was to the fundamental, underlying laws of mechanics. As we’ll see, electricity and magnetism are evident everywhere in our world, especially in our technology but also in basic structures.
- II. In Newton’s day, electricity was a curiosity. People were aware of the phenomenon of static electricity but didn’t begin to investigate it scientifically until about 100 years after Newton.

- A. We're all familiar with static electricity. Think of walking across a carpet, touching the doorknob, and getting a shock or pulling apart clothes that have just come out of the dryer. Whenever anything sticks together, like the clothes, that implies a force of nature, and in this case, the force is not just friction.
- B. Let's investigate static electricity using a simplified approach.
1. Benjamin Franklin (1706–1790) helped start us on the path toward our current model of electric charges. In addition to flying the kite in the electrical storm, Franklin conducted experiments in which he rubbed various objects together, such as cat fur on amber or glass rods.
 2. Try a similar experiment on your own: Take about a foot of tape and fold over the ends to make tabs for pulling the tape up. Label this piece of tape *b* for “bottom.” Place a second piece of tape on top of the first and label it *t* for “top”; then, stick both pieces of tape, now stuck together, down on a flat, clean table. Next, duplicate the experimental setup. Play around with the tape by ripping it off the table, then ripping the two pieces apart.
 3. It will be immediately obvious that the pieces of tape are charged. You'll also discover that different things happen to the top tape and the bottom tape. Two top tapes, for example, will repel each other, but a top and bottom will attract.
- C. Let's construct a simple model to help us describe and understand the basic phenomenology of static electricity.
1. Recall our discussion of what a model is: a simplified, descriptive picture. It must be consistent with known experiments and lead us to predictions about future experiments.
 2. In the accepted model of electricity and magnetism, the world is made of atoms that carry electric charge. Electric charge is the quantity that exhibits the force of static electricity.
 3. The tape experiment shows us that we need two types of charge to explain the results. Ben Franklin named these types of charges *positive* and *negative*.
 4. How did Franklin know that there wasn't a third type of charge? Ockham's razor (named for a medieval philosopher, William of Ockham) suggests that we use the simplest explanation to understand complex phenomena. In other words, we don't add another charge because we aren't required to by the data.
- D. Franklin's choice of *positive* and *negative* for the names of the two charges is helpful to our understanding of electricity, because it leads us to think of adding *plus* and *minus* charges. When we add positive and negative charges, the net charge is zero.

- E. According to our model, the world is filled with positive and negative charges, and as we deduce from the tape experiment, opposite charges attract and like charges repel.
- F. Newton saw that the gravitational force between two masses arises because of the mass. In the same way, the electrical force arises because of the charge. As we'll see in an upcoming lecture, we find the strength of the electrical force by multiplying the charges. Again, with multiplying, the positive and negative sign convention neatly summarizes the fact that opposite charges attract and like charges repel.
- G. Our model is predictive and explanatory, but it doesn't tell us what charge is; it only postulates that charge exists.
 - 1. With our model, you can see that combing your hair separates charges; the comb becomes negatively charged and your hair becomes positively charged. Your hair stands on end because all those like charges are repelling one another.
 - 2. You can also understand why a balloon will stick to you after you rub it on your shirt, but why does it stick to the wall? The answer is that the wall also has electrical charges in it. Any negative charges in the wall that are free to move will be repelled by the balloon; any positive charges in the wall that are free to move will be attracted to the balloon. Separation of charges takes place again.
- H. In one respect, Franklin's naming convention may be slightly confusing: We now use the term *electrons* for particles that carry negative charges, and these are the particles that move most easily in nature, although we might tend to associate positive charge with movement. Nonetheless, the simple story of static electricity has been spectacularly useful

III. Let's turn briefly to magnetism.

- A. Find a child's set of magnets and experiment with them on your own. You'll find that magnetic force is quite similar to electric force. Instead of positive and negative charges, we say that magnets have *north* and *south poles*, which attract and repel each other analogously to charges.
- B. One difference between magnets and static electricity is that magnetism seems to be permanent, whereas static electricity tends to fade with time for ordinary objects.

IV. We now have only a very basic understanding of static electricity. In future lectures, we'll see that the lightning bolt that Franklin was investigating; forces of nature, such as friction; and the high technology we now use all arise simply from the postulation of positive and negative charges and the electrical forces (ultimately, using Newton's law) between them.

Essential Computer Sim:

Go to <http://phet.colorado.edu> and play with Balloons and Static Electricity and John Travoltage. Do the balloons behave realistically? Are they conductors or insulators? How about the walls? Is charge flowing in the walls? Can you understand why the balloons stick to the wall, even though the total charge of the wall is zero? Why doesn't John Travoltage generate a spark immediately? Why does he have to build up some charge first? What role does the doorknob play? Why do you need it?

Essential Reading: Hewitt, start of ch 21, Hobson, ch 8.4, March, start of ch 6.

Recommended Reading: Gonick, chapter 12.

Questions to Consider:

1. Suppose somebody proposed to you that we are attracted to the Earth, not because of gravity, but because of static electrical forces. How could you convince this person that he or she is incorrect?
2. Try the tape experiment described in the lecture. What variations can you come up with? Can you determine which piece is positive and which is negative? Can you explain all your observations by hypothesizing only two charges (positive and negative), or do you need more?
3. Buy some toy magnets—not kitchen magnets but small bar magnets with two clear poles, like the plastic-coated, super-strong magnets that come with ball bearings as in a child's building kit. How are these magnets the same as and how are they different from the charged tapes? Can you prove that they are not attracting and repelling because of forces of static electricity? Can you build a compass out of these magnets?
4. Suppose that Ben Franklin had reversed his choice of which material to call *plus* and which to call *minus*. Would this change any of our laws of physics? What would be different?

Lecture Fourteen

Electricity, Magnetism, and Force Fields

Since Maxwell's time, physical reality has been thought of as represented by continuous fields, and not capable of any mechanical interpretation. This change in the conception of reality is the most profound and the most fruitful that physics has experienced since the time of Newton.

—Albert Einstein

Scope: In the last lecture, we introduced a “new” force in nature, electricity, and we constructed a model in which there were two kinds of electric charge, positive and negative. *Electric charge* is a term we used to describe the source of the static electrical force. Using our model, we saw that like charges repel each other and opposite charges attract. In this lecture, we’ll move away from thinking of electric charge as “action at a distance,” as Newton did, and begin thinking about electrical *fields*. This concept will help us to understand electricity better and to reformulate the way we think about gravity. The key player in the origination of the mathematical theory of static electricity was Charles Coulomb, a French scientist and engineer working in the 1780s. Coulomb’s experiments with static electricity were similar to those conducted by Henry Cavendish to measure the force of gravity. We’ll also look at the work of Michael Faraday, the British physicist who introduced the concept of a force field, and we’ll see how this idea allows us to dispense with action at a distance and visualize force as a local phenomenon.

Outline

- I. Charles Coulomb (1736–1806) discovered the fundamental mathematical relationship describing static electrical forces in the 1780s.
 - A. To understand the gist of Coulomb’s experiments, imagine charging up a balloon by rubbing it on your shirt. You’ll discover that the charges on the balloon tend to stay put. The side of the balloon that you rubbed will be highly charged; the other side of the balloon will not be any more charged than it was to begin with. In physics, the balloon would be called an *insulator*, that is, an object in which charges can’t migrate easily. Metals have the opposite property; in metals (*conductors*), charges spread out easily.
 - B. Coulomb experimented with metal spheres, which allowed him to distribute charges and measure the forces between them.

- C. In honor of Coulomb's work, electric charge is measured in units called coulombs. One coulomb (1 C) is a significant amount of electric charge; a balloon rubbed on your shirt might have only $1/1,000,000$ C

II. Let's look back again at the force of gravity.

- A. Masses cause a gravitational attraction, and the force of gravity is a constant of nature (measured by Cavendish) multiplied by the mass of one object times the mass of a second object, divided by the square of the distance between the two objects.
- B. Coulomb discovered that electricity could be described in much the same way, using the idea of charge rather than mass. Multiplying the charge on one object (measured in coulombs) by the charge on a second object will tell us how strong the force is between those two objects. Coulomb also discovered that static electrical attraction or repulsion, like the force of gravity, declines with greater distance between the two charged objects.
- C. There are some similarities between the force of electricity and the force of gravity, but the two forces are *not* the same thing. For instance, in considering the force of gravity, we know that all masses attract, but with electricity, both attraction and repulsion take place.

III. Like Newton's law, Coulomb's law was still a description of mysterious "action at a distance," which Newton himself was not comfortable with. The resolution to the problem of two unconnected objects somehow influencing each other was the idea of a *force field*, introduced by a British physicist, Michael Faraday (1791–1867).

- A. Faraday was originally a bookbinder. His lack of formal mathematical training compelled him to think of visual ways to describe and understand complex phenomena, such as electricity and magnetism.
- B. Let's also use a simple picture to think about the idea of a force field: Imagine a mattress with a heavy bowling ball in the middle; the bowling ball is the *source* of a force.
 - 1. The mattress sags in the middle; that is, the mattress curves down and inward in all directions toward the bowling ball. The curved surface of the mattress offers some potentiality of force. We could verify this potentiality by placing a marble on the edge of the mattress and watching it roll toward the center.
 - 2. Next, we could place the marble at different points all around the mattress and draw arrows to represent the force created by the source (the bowling ball).
 - 3. If we remove the marble, what we have left are arrows drawn on the mattress, which represent a *force field*. Nothing is happening on the mattress, but the possibility is there, and if we placed the marble on the mattress again, something would happen. In other words, a force field exists, whether or not we test it.

- C. We can extend this example to a gravitational field.
 - 1. Instead of a bowling ball on a mattress, think of the Sun in the middle of the solar system. If we let go of a test mass near the Earth, it would be pulled toward the Sun. We could again draw arrows in three-dimensional space, which would all point toward the Sun.
 - 2. Even if we remove all the planets from the solar system, the gravitational force field still exists, whether or not a test mass is available to show it.
 - D. The electrical field is a slightly more abstract way of characterizing electrical forces.
 - 1. A balloon rubbed on your shirt can serve as a source of an electrical field. In this case, we have to use a test charge, rather than a test mass, to see the effects of the electrical field. If both the balloon and the test charge are positive, we would draw an outward-pointing arrow to represent their repulsion.
 - 2. The force felt by the test charge depends on how strong the test charge itself is. This idea is akin to unit prices in grocery stores. A grocery store might have a unit price of \$2.00 per pound for beans. This "price field" exists throughout the store, but doesn't tell you how much you will pay for beans at the checkout counter. The price you pay depends on the size of the bag of beans you choose. In the same way, the strength of the attraction or repulsion felt by the test charge depends on the magnitude of its charge.
 - E. Faraday simplified the picture of a force field by replacing the arrows with lines drawn away from the charges. For a point charge, this is called a *radial field* because all the lines resemble the radii of a circle.
 - 1. Such a picture gives us an intuitive idea of the physics of a field. For example, the strength of the field is represented in this picture by how closely spaced the lines are.
 - 2. If we had a positive charge at one point and a negative charge at another, the field line diagram would become more complicated.
 - F. We could also map out a magnetic field. In this case, the tester would have to be another magnet, perhaps a compass needle.
- IV. The idea of fields is powerful because it gives us a fresh way of thinking about force that doesn't involve action at a distance. With the idea of fields, we can consider force as a local phenomenon, and we can predict the strength and direction of the force on any object at any point in the field.

Essential Computer Sim:

Go to <http://phet.colorado.edu> and play with Electric Field Hockey (EFH) and Charges and Fields. EFH will give you a sense of the force on a charge. Keep it simple at first; try to make sense of the connection between the field and the

motion. Think back to earlier examples—the force determines the acceleration (not the velocity). Can you arrange charges to make the test charge (the one that can move) do what you want? Notice the Field button at the bottom. When you turn that on, does the result make sense to you? For Charges and Fields, show only the E field (don't bother with V, for voltage, just yet). Add some charges and move them around. What does the “intensity” of the red arrows indicate? (Does that match with what you see when you add an E field sensor? Why is the length of the sensor arrow different from the usual red arrows?)

Essential Reading:

Hewitt, rest of chapter 21.

Hobson, chapter 9.1.

March, middle of chapter 6.

Recommended Reading:

Cropper, chapter 11.

Gonick, chapters 13 and 17.

Questions to Consider:

1. How would you experimentally distinguish an electrical field from a gravitational field? From a magnetic field?
2. You and I both set out to map out an electrical field in the laboratory. I use a test charge of 1 microcoulomb, and you use a test charge of 2 microcoulombs. If we both independently “test” the same point in the room, will we agree *numerically* on the value of the electrical *force* on our test charges? (If not, how will the forces be related?) Will we agree *numerically* on the value of the electrical *field*?
3. An electron and a proton are placed in an identical electrical field. Compare the electric forces on each of them. Compare the resulting acceleration on each of them (direction and “how big,” relatively). (Note: Electrons have negative electric charge and are very light. Protons have positive electric charge of the same magnitude as the electron but are very heavy.)
4. What would it mean to say, “An electrical field is real”? What (if anything) does “real” mean, when you’re thinking like a physicist? Can you ever see a field? Feel it directly?

Lecture Fifteen

Electrical Currents and Voltage

...after Faraday was made a fellow of the Royal Society[,] the prime minister of the day asked what good this invention could be, and Faraday answered:

“Why, Prime Minister, someday you can tax it.”

—Frequently referenced but probably apocryphal quote

Scope: In the last lecture, we saw that an electric charge, acting as a source, creates a field in space, to which other charges respond. In this lecture, we'll look at the progress made in the 19th century in applying this understanding, which resulted in batteries, devices for storing charge, and simple circuit elements. Today, our lives are surrounded by electrical (and electronic) devices. The critical distinction (and connections) between voltage and current allows us to make intuitive sense of much contemporary electrical technology and phenomena.

Outline

- I. Nineteenth-century progress in the understanding and applications of electricity was rapid and deep. As a direct result, electrical devices have become a significant part of our contemporary lives.
 - A. The language of simple electrical devices requires understanding the concepts of *circuits*, *current*, and *voltage*.
 - B. Our goal in this lecture is to build a mental model to answer questions about electricity, such as: What is electricity? How do we guide and control it? How can we understand manifestations of electricity, such as light coming from a light bulb, in terms of our underlying picture?
- II. Let's begin with a couple of familiar terms: *insulator* and *conductor*.
 - A. Electric charges constitute a property of material objects; in other words, material objects have charge on them. As mentioned in the last lecture, in some materials, such as a balloon, that charge tends to stay in one place, and in other materials, such as metals, the charge is allowed to flow. If the charge flows, the material is a *conductor*; if the charge is “stuck,” the material is an *insulator*.
 - B. Air is an example of a material that acts largely as an insulator. If we build up electric charges on a piece of tape, they will tend not to drift through the air. However, if we build up enough static charge in one spot, the electrical force between the charges can eventually push some charges into the air.
 1. With enough energy, an electric charge in the air can rip atoms apart. The atoms will later recombine (because the opposite charges attract each other) and release energy.

2. That release of energy can take a number of forms, including a spark of light. This is the phenomenon we see in lightning bolts and in the spark produced when you walk across the carpet and touch another person or a metal doorknob.

- C. Another term we need in discussing electricity is *ground*, which we can use in both the standard English sense and a technical physics sense. The ground is a place for charges to spread out and neutralize.

III. How can we harness the flow of electrical charges for practical applications?

- A. We need a mechanism to both build up charge and provide a conducting path back to the ground. The result is an electrical circuit.
- B. In 1800, Alessandro Volta (1745–1827) discovered a simple setup of materials that served as an electrical “pump”—the first battery. The materials inside batteries separate charges and drive them to one end or the other. The minus sign on a battery means that negatively charged electrons are driven to that end. The plus sign means that positively charged ions are being driven to the opposite end of the battery.
- C. To use the battery, you need a connection, such as a wire, between the negative and positive ends; you can then sustain a flow of charges.

IV. Consider another metaphor to think about electrical circuits and the idea of voltage.

- A. Imagine a device that lifts up bowling balls, similar to the return mechanism in a bowling alley. Our device lifts bowling balls up in energy. The term *voltage* is roughly a reference to energy in electrical circuits, that is, how high we’re lifting the bowling balls.
- B. The height to which we lift the bowling balls (to the tabletop versus to the attic) tells us how much work they’re going to be able to do when we let them fall back down again.
- C. If we pump up an electric charge, we’ve added energy to that electric charge, just as we’ve added energy to the bowling balls by lifting them to the attic. *Voltage* is defined as energy per charge, or energy per coulomb. Specifically, 1 volt refers to 1 joule of energy per coulomb.
- D. A car battery is 12 volts. This means that 12 joules of energy is required for every coulomb of charge moved from one pole of the battery to the other. Every coulomb that flows through the wire connecting the positive pole to the negative pole yields 12 joules of energy.

V. In addition to voltage, we need to understand the concept of *current*.

- A. With our bowling-ball machine, we need to know how many bowling balls we lift and let fall down every second. If we lift and let fall 10

balls per second, we will get a lot more work from the device than if we lift and let fall only 1 ball per second.

- B. *Current* refers to the flow rate: how many charges flowing per second.
- C. Instead of bowling balls, we can think of a water pump, moving water up into a reservoir. The height of the reservoir (the voltage) is significant. If we can pump the water up to a higher level, we will store more energy per gallon. The other important aspect of this system is how many gallons are flowing per second (the current).
- D. The measure used for current is *amps*, named after André Ampère, whom we'll meet in a later lecture. One ampere of current flow is 1 coulomb flowing every second.
- E. With real water pumps, the amount of water that will flow each second depends on the pipes that are used. A large pipe allows lots of water to flow through; a skinny pipe introduces more friction—*resistance*—and doesn't allow as much water to flow. The same is true of electricity: A thick wire allows relatively easy flow of electricity.
 - 1. The term *resistor* is used (unfortunately) for materials that are both highly resistive and not so resistive.
 - 2. We can think of resistance as adding friction to a circuit. As current flows through resistors, they dissipate energy and heat up.

VI. When we use electricity, we often need some kind of a pump. We've talked about using a battery as a pump, but the wall socket is also a kind of pump.

- A. The two main prongs of a plug are rather like the poles of a battery; they, too, have a plus side and a minus side (which alternate in time).
- B. When you plug in an appliance, the electricity flows through the two prongs, forming a complete circuit.

VII. What is dangerous about electricity?

- A. High voltage by itself is not intrinsically dangerous. It's like having bowling balls in the attic; if the floor is strong enough (like a battery with a good insulator), preventing the flow of the bowling balls, there's really no danger at all.
- B. If a bird lands on a high-voltage power line, it's in no danger. The danger would come if the bird were to stretch its wings and connect the power line with the ground. That opens up a conducting path for the charges to flow through the bird.
- C. Multiplying voltage (energy per charge) by current (charge per second) yields energy per second, or power. High voltage, then, is potentially dangerous because it can yield a high rate of energy per second.

VIII. Every electrical device in your house is designed around these basic ideas, and again, we can trace this discussion back to Newton and his concepts of force—pushing and pulling charges—and energy.

Essential Computer Sim:

Go to <http://phet.colorado.edu>, build circuits with the Circuit Construction Kit, and play with Charges and Fields again (this time, turning on the voltage indicator). Where is the voltage high, and where is it low? The Circuit Construction Kit (CCK) is my favorite sim. You can spend a lot of time with it, getting a sense of, and the connections among, voltage, current, and power. Try to answer question 1 below with the CCK! There are many more sims to play around with, which I leave up to you to investigate, including: Battery Voltage, Resistance in a Wire, Ohm's Law, Battery-Resistor Circuit, and Signal Circuit.

Essential Reading:

Hewitt, rest of chapter 21 and chapter 22.

Recommended Reading:

Gonick, chapters 15–16.

Questions to Consider:

1. Dig up a small bulb (e.g. from a flashlight), a battery, and a single piece of electrical wire. Can you make the bulb light? Once you have done so, try to find at least four different arrangements that light the bulb. How are they similar? What is the requirement for the bulb to light? What can you conclude about how the bulb is “wired up” inside, where you can’t see it?
2. It’s easy to confuse *voltage* and *current*. What is wrong with a news broadcaster saying, “20,000 volts of electricity flowed through the victim’s body”? What language would you use to describe this tragic accident more accurately? In the end, what harms an electrocution victim, the voltage or the current (or something else)?
3. You have two glowing light bulbs. One is rated 100 watts (which means 100 joules/sec), and the other is rated 20 watts. What is the same, and what is different, about these two bulbs and the electrical flow through them? (Is the power the same or different? Current? Voltage?) What can you say about how much “resistance” each one offers? (This is tricky! A clue is that wall sockets in the U.S. are 120 Volts, no matter what you plug into them.)
4. When you get the bill from your power company, what do you pay for, electric power or electrical energy? How are these related? Look at your electric bill. Odds are that it tells you how many kWh, or kilowatt hours, you are paying for (1 kilowatt means 1000 watts, which is 1000 joules each second). Note that kWh is *not* kilowatts *per* hour! It is kilowatts *times* hours. If you can make sense of why your power company charges you for kWh, you’ll have mastered the big ideas of power and energy from this lecture!

Lecture Sixteen

The Origin of Electric and Magnet Fields

Aye, I suppose I could stay up that late.

—James Clerk Maxwell, on being told on his arrival at Cambridge University that there would be a compulsory 6:00 a.m. church service

Scope: Despite all our wonderful technologies, electricity and magnetism are forces we only rarely experience *directly* (e.g., static cling or kitchen magnets). These two forces are distinct but intimately connected. We can create (electro)magnets out of completely nonmagnetic materials, making use of pure electric currents. And we can produce electrical currents by spinning magnets near wires. In this lecture, we zoom in on the *sources* of electric and magnetic fields and their myriad connections, leading to a deeper understanding of the unity of electromagnetic physics.

Outline

- I. Let's begin this lecture by talking about magnets; specifically, we'll look at the commonalities and differences between electricity and magnetism.
 - A. Magnets have two poles, north and south. As with electric charges, like magnetic poles repel each other and opposite magnetic poles attract.
 - B. This phenomenon looks like action at a distance, but if you hold two magnets close together, you can almost feel the force field operating between them. A compass needle, which is a small magnet, responds to the magnetic field, just as a test charge responds to electrical fields.
 - C. You can map out a magnetic field by placing a piece of paper over a magnet and sprinkling iron filings on the paper. The filings will arrange themselves in a field line pattern, showing magnetic fields looping from north to south poles.
- II. What are the differences between electricity and magnetism?
 - A. You can charge materials up electrically by rubbing them, but the same thing doesn't work for magnets. Most materials are not magnetic.
 - B. Magnets stay magnetic for a long time.
 - C. Compass needles do not deflect in the presence of electric charge. In other words, magnets are neither attracted to nor repelled by electric charge. This alone tells us that electricity and magnetism are two distinct forces of nature.
 - D. By the same token, electric charges are not attracted to magnets. The Earth is a giant magnet, which causes all compass needles to point north. But there is no attraction of electric charges to magnets.

- E. Electric charges can be separated, but magnetic poles can not.
 - 1. I could charge up a balloon, hand it to you, and you could walk away with it; you would then have an isolated electric charge.
 - 2. If you cut a magnet in half, however, you would not end up with an isolated north pole or an isolated south pole; you would have two smaller magnets, *each* with a north pole and a south pole.
 - 3. If you *could* isolate a magnetic pole, scientists would call that a *magnetic monopole*.
- F. The bottom line is that electric charges interact with other electric charges, magnets interact with other magnets, and masses interact with other masses. Thus, all three forces at work here—electrical, magnetic, and gravitational—seem at first to be independent and unrelated.

III. In the early 1800s, Hans Oersted (1777–1851) discovered, while preparing for a classroom lecture, that electrical currents can produce magnetic fields.

- A. This discovery was a surprise. Electric and magnetic fields were assumed to be separate and distinct; Oersted found that flowing electric charges in a simple circuit create a magnetic field. Oersted's simple, reproducible experiment generated significant interest.
- B. Merely closing a switch to allow current to flow creates a magnetic field, and can lead to practical applications.

IV. The French mathematician André Ampère (1775–1836) began to formulate a law to explain magnetic fields.

- A. As we said earlier, static electric charges (that is, charges that are not moving) create electrical fields. The field lines in our earlier picture emanate in straight lines from (or toward) electric charges in the center.
- B. With magnetism, you might think that the pattern of field lines created by an electric current would be similar; that is, you might expect to see radial magnetic field lines pointing away from a current-carrying wire. However, magnetic field lines run in circles around the electric current.
- C. In thinking about this phenomenon, keep in mind that electric charge is flowing, but the field is static. Ampère worked out the mathematics to predict the magnetic field generated from any current in any strength.
- D. You could run an experiment at home to create a magnetic field, although you would have to exercise some caution. You would also have to take into account the fact that the Earth has its own magnetic field; you would be superposing your magnetic field on the one that already exists on the Earth. What would be the result of this superposition?
 - 1. Recall Galileo's superposition principle applied to forces: Two forces acting in opposition will cancel each other out; two forces acting in the same direction will add up.

2. If the magnetic field you create is aligned with the Earth's magnetic field, the resulting magnetic field will be stronger. If the magnetic field you create points in the opposite direction of the Earth's magnetic field (and is equally strong), the result is no magnetic field at all.
- V. One very strange aspect of electricity and magnetism is that static electric charges don't generate magnetic fields, but moving electric charges do.
- A. If I charge up a balloon and place it in a room, no magnetic field is generated. But now you enter the room in a slightly different reference frame, moving steadily through the room on a cart. From *your* reference frame, you are at rest, and the room is sliding by you at 2 meters per second. To you, the balloon is moving, which means that electric current is flowing, and a magnetic field is created.
 - B. Electric and magnetic fields are very real and intimately connected, but the value and nature of the fields are dependent on the observer. Ultimately, physicists will give the name *electromagnetism* to this one force of nature, which seems to have two sides to it.
- VI. Let's return now to applications.
- A. A certain amount of current will create a certain magnetic field strength. Doubling the current will also double the field strength. You can make a very powerful magnet simply by running current through coils of wire.
 - B. When you insert a key in your car, you complete a circuit that starts electricity flowing through a coil of wire (the solenoid). The resulting magnetic field is strong enough to pull an iron rod, engaging the starter.
- VII. Where does the magnetic field of an ordinary kitchen magnet arise from? No obvious current is flowing to generate a magnetic field.
- A. In fact, there is current in this situation, but it's microscopic. The full story requires modern quantum physics, but we can make basic sense of it with a simplified classical physics picture.
 - B. An atom of any material has a positive, heavy nucleus and negative electrons in orbit around it. The moving electric charge of the electrons constitutes a current. This current creates a tiny magnetic field; thus, atoms themselves are tiny magnets.
 - C. If nearby atoms are randomly oriented, the magnetic fields they produce will cancel. That's why ordinary materials aren't magnetic. But in special materials—such as iron crystals—the magnetic fields of the atoms align; adding these microscopic fields up creates a macroscopic magnetic field.

VIII. Faraday discovered moving magnets generate electrical fields, perhaps the most practically important discovery in the history of physics. Rotating magnets at a power plant are the source of the electrical field that pushes electrons through your toaster oven or computer.

Essential Computer Sim:

Go to <http://phet.colorado.edu> and play with Faraday's Electromagnetic Lab. There are tabs for different experiments. Look at the magnetic field; do you understand this representation of the field? The Pickup Coil variation lets you directly study Faraday's law of induced currents. In Electromagnet mode, turn up the voltage and see if you can visualize the circles of magnetic field around the coils.

Essential Reading:

Hewitt, chapters 23–24.

Recommended Reading:

Cropper, chapter 12.

Gonick, chapters 18–19 and 21–22.

Questions to Consider:

1. Opposite magnetic poles attract (north attracts south). A compass needle is a tiny magnet, and (by convention) we label the pole that points toward geographic north (Canada) the “north” end. (Seems reasonable; magnetic north points you geographically north!) Now think carefully (draw a picture) and decide which magnetic pole of the giant magnet that is planet Earth is the one located in northern Canada. (The answer may surprise you.)
2. Can a constant (steady, unchanging) magnetic field set into motion an electron initially at rest? Try to explain your reasoning carefully.
3. Particle physicists send high-energy microscopic particles through *bubble chambers*, where they leave a trail of bubbles as they pass, enabling physicists to track their motion. There is always a strong magnetic field in the bubble chamber, and some particle tracks form spirals, while others are straight lines. What can you conclude is different about these particles?
4. Iron is a magnetic material, but it is not always a “magnet.” Most pieces of iron have no poles, but a magnet sticks to it. (Your refrigerator has iron in it that is not itself magnetized, but a magnet will attract to it.) Let's say I hand you two heavy, identical chunks of iron, one of which is magnetized, and the other is not. Think of at least three different ways you might figure out which one is the natural magnet and which is unmagnetized iron.

Lecture Seventeen

Unification I—Maxwell's Equations

From a long view of the history of mankind— seen from, say, ten thousand years from now, there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics. The American Civil War will pale into provincial insignificance in comparison with this important scientific event of the same decade.

—R. P. Feynman, *Lectures on Physics*, Vol. II

Scope: In the last lecture, we saw that electricity and magnetism are different forces of nature, but they seem to be connected in certain ways. For example, a moving magnet produces an electrical field and vice versa—a moving electric charge produces a magnetic field. In this lecture and the next, we'll refine our understanding of these forces and their connection. The unification of electricity and magnetism is one of the grand intellectual achievements of classical physics. The person credited with this synthesis is James Clerk Maxwell, a Scottish physicist working in the mid-1800s, who organized the work of Ampère, Coulomb, Faraday, and others into four simple equations that constitute the "rules" of electricity and magnetism. In the end, Maxwell was able to summarize everything we know about electromagnetism in a set of four relations, two for static situations and two for time-varying situations. Together with Newton's laws, these relationships quantify all electric and magnetic phenomena. In this lecture, we'll bypass the mathematics of Maxwell's equations and try to understand the underlying essence of each one.

Outline

- I. The first of Maxwell's equations is similar to Coulomb's law; it describes electrical fields arising from electric charges.
 - A. Maxwell combined Coulomb's work with that of a German mathematician named Carl Friedrich Gauss (1777–1855). *Gauss's law* involves looking at the outside of a region with an electrical field to deduce the nature of the sources inside. Think of encasing an electric charge in a bubble and observing the electrical field lines emanating from that source. If field lines are pointing outward in all directions, we can conclude that there must be a charge inside the bubble.
 - B. Gauss's law is intuitive: Electric charge is the source of electrical fields, which emanate from the source. The same is true in reverse: If we see electrical fields pointing outward in all directions, we know that they must be emanating from a source.

- C. Gauss's law is both quantitative and qualitative: It tells us how strong the electrical field is and what pattern it produces. Gauss's law is also more robust than Coulomb's law. It accounts for multiple electric charges and for moving charges.
- D. Gauss's law is universal, requiring a fundamental constant of nature (measured by Coulomb). This constant is necessary to determine how strong the electrical field is for a given amount of charge.
- E. A dog sniffing around a barbeque grill can conclude that the smell of cooking food is emanating from the grill as a source. Gauss's law can be thought of in the same way.

II. The second of Maxwell's four equations is sometimes called *Gauss's law for magnetism*.

- A. This is a sort of negative law. If we encase a magnetic field in a bubble, we will *never* see field lines emanating from a source in the middle. In other words, there are no point-like sources of pure magnetic field lines in the universe—no magnetic monopoles.
- B. Even though this law is negative, it tells us something about the pattern for all magnetic fields in the universe: They never emanate from a point; they run in circles, never stopping or starting at points in space.
- C. Physicists have sought to falsify Gauss's law for magnetism (by finding a magnetic monopole) for 150 years, without success.

III. The third of Maxwell's four equations is also called *Ampère's law*.

- A. As mentioned in the last lecture, Ampère's law tells us that a current (flowing electric charges) generates a magnetic field. Ampère's law is a rigorous description of this phenomenon, a mathematical formula that can be used to calculate the strength and direction of the magnetic field, just as Gauss's law can be used to determine the strength and direction of the electrical field.
- B. Again, Ampère's law requires a numerical constant of nature to characterize the connection between the amount of electric current flowing and the strength of the magnetic field.

IV. The fourth of Maxwell's equations arose from Faraday's work and is usually called *Faraday's law*.

- A. As we mentioned in the last lecture, Faraday realized that a moving magnetic field generates an electrical field; in turn, electric charges will respond to this field.
- B. Faraday's law is the most directly practical and widely used of all the equations described so far. Sometimes called the *law of electrical induction*, it accounts for how we produce electricity in our homes and how we convert electrical voltages (via transformers) for such devices as laptop computers and cell-phone chargers.

- V. In looking at these equations, Maxwell noticed an aesthetic “hole,” a lack of symmetry.
- A. According to Ampère’s law, flowing electric charges create magnetic fields. At the same time, according to Faraday’s law, changing magnetic fields produce electrical fields. If that’s true, why wouldn’t changing electrical fields produce magnetic fields?
 - B. To resolve this problem, Maxwell took a leap and hypothesized an additional term in Ampère’s law, designed to make it symmetrical with Faraday’s law. In making this leap, Maxwell drew on the rich tapestry of data from existing experimental and theoretical physics and realized that his hypothesis would have to stand up to the tests of mathematical and physical consistency, consequences, and falsifiability.
 - C. It took many years for Maxwell’s addition to Ampère’s law to be directly tested through experiment, but once it was, numerous practical applications were realized.
 - D. We now have two ways to produce a magnetic field, but why don’t we have two ways to produce an electrical field? The answer: There are no flowing magnetic charges—no magnetic monopoles—in the universe.
- VI. Maxwell’s four equations enable us to understand the patterns of electrical and magnetic fields in any circumstances. Let’s summarize them.
- A. Static charges generate static electrical fields that show a radial field pattern, but there is no analogous source for magnetic fields because there are no magnetic monopoles.
 - B. Moving electric charges generate circular magnetic fields; further, a moving electrical field also produces a magnetic field.
 - C. Finally, a moving magnetic field produces an electrical field.
- VII. Maxwell’s equations focus on fields, leading us to think of nature, as we do today, in terms of field theory.
- A. These equations are enormously practical. They tell us how to design devices ranging from a cell-phone antenna to a toaster oven.
 - B. Further, all of Maxwell’s equations tie in with Newton’s laws and help us see fields as “real.” The equations fit beautifully with the classical physics worldview, enabling local, deterministic, and quantitative predictions and explanations.

Essential Computer Sim:

Go to <http://phet.colorado.edu> and play with Faraday’s Electromagnetic Lab (check out the Transformer and Generator tabs if you haven’t already). Then look at Radio Waves and Electromagnetic Fields. Can you understand the various representations of an electrical field? Which of Maxwell’s equations are involved?

Essential Reading:

Hewitt, review chapters 21–24 (it's all there).

Hobson, start of chapter 9.

Recommended Reading:

Cropper, chapter 12.

Gonick, start of chapter 23.

Questions to Consider:

1. If magnetic monopoles existed in nature, what changes would we have to make to Maxwell's equations? Which equations would be modified? Would there be a new constant of nature to measure?
2. I have argued that Faraday's law (which states that any change in the magnetic field through a coil will generate electric currents) has had enormous technological impact, specifically with regard to electrical generation and transformers. What other pieces of everyday technology make use of Faraday's law? (Think of devices in your home, in your car, at the airport...) The list is quite long; can you come up with a half-dozen?
3. We have said that electric currents generate magnetic fields. Is there a measurable magnetic field near, say, the cord leading to a lamp in your house? (If not, why not?) We have said that *changing* the electrical field over time also generates magnetic fields. Since the current in the lamp cord is AC (alternating current, flowing back and forth), would *that* generate a measurable magnetic field? Why or why not?
4. Static charges feel a force only from electrical fields. Moving charges feel forces from magnetic fields, as well. This fact forms the basis for electric motors: You use electrical fields (e.g., from a battery) to run current through a metal loop situated in a static magnetic field. The current (moving charges) feels a force from the magnetic field and is pushed—it turns. That's all there is to any electric motor. What happens if you take the exact same device but disconnect the battery? What happens if, with the battery disconnected, you physically rotate the metal loop in the presence of this magnetic field? What important device have you just created?

Lecture Eighteen

Unification II—Electromagnetism and Light

And God said:

$$\nabla \cdot E = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot B = 0$$

$$\nabla \times B = \mu_0 J + \mu_0 \epsilon_0 \frac{\partial E}{\partial t}$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

and there was light.

—Maxwell's Equations on a t-shirt popular at MIT when I was an undergraduate

Scope: Maxwell's equations synthesize and describe every aspect of classical electromagnetism, from lightning bolts, to electric circuits, to kitchen magnets. But Maxwell made another observation that went far beyond his original equations: He discovered they predicted a “new” phenomenon, an electromagnetic traveling wave, ultimately recognized to be light. All of optics, the remaining great branch of physics, was suddenly completely and deeply unified with electric and magnetic phenomena. Maxwell had provided a grand synthesis of all known fundamental forces of that era (*besides* gravity), allowing us to make sense of the spectrum of radiation and an enormous span of physics, as well as setting a compelling tone for ongoing physics research.

Outline

- I. The most common motion in the universe is oscillation. The Earth, an atom, and a pendulum all oscillate. Maxwell asked: How would an electric charge behave if it were moving in this most common way?
 - A. A static electric charge (an electron) generates an electrical field with straight lines pointing, in this case, in toward the charge. You might think of these lines as similar to the gravitational field lines pointing in toward a star.
 - B. As the charge moves back and forth, the electrical field lines must move also in order to constantly point toward the charge.
 - C. A moving electrical field, according to Maxwell's “extra term,” will produce a magnetic field; the resulting magnetic field will oscillate.

- D. According to Faraday's law, a changing magnetic field will produce an electrical field.
- E. The original source in this system was a charge, which created an electrical field, which in turn, created a magnetic field, which in turn, created an electrical field, and so on.
 - 1. We can visualize this phenomenon by thinking of a pebble dropped into a pond. The pebble (the original charge) starts a disturbance (a wave) in the water that is self-propagating.
 - 2. In Maxwell's case, there is no water or other medium. The ripples from the original charge are fields in otherwise empty space.

II. These fields exist, but we have to think about them mathematically.

- A. We can find evidence for the existence of electrical and magnetic fields. Can we find similar evidence for the self-propagating phenomenon that Maxwell discovered?
- B. We already know that we can detect the oscillation of an electrical field by looking for a similar oscillating response in a test charge.
- C. Maxwell found that he could calculate the speed of propagation of an electromagnetic wave. The wave travels at a speed that is dependent on the two constants of nature from Maxwell's original equations. In fact, the answer turns out to be 300 million meters, or 186,000 miles, per second—precisely the speed of light!
- D. This result implies that the electromagnetic disturbance we've been talking about is light; light is nothing more than a traveling electromagnetic wave.

III. Maxwell's discovery unified electricity, magnetism, and light.

- A. Think about a light bulb. When the filament gets hot, the electrons inside begin to move, producing an electromagnetic wave that travels outward. The electrons in your retina respond to this wave as it passes, because an electrical field always moves charges around. The moving charges in your retina, in turn, send electrical signals to your brain. As we know, our brains respond only to a certain narrow range of frequencies of these oscillations in the retina, and we "see the light."
- B. At this point, we understand the nature of light and optics and that the electromagnetic wave of Maxwell's equations is not exotic at all.

IV. Maxwell published his work over several years around 1860, but it took 20 years for the scientific community to accept this revolutionary synthesis.

- A. Experimental verification came with the work of a young German physicist, Heinrich Hertz (1857–1894). Hertz built an electric circuit called an *oscillator*, designed to allow current to flow back and forth. He then built another oscillator, similar to the first one but with no power supply. According to Maxwell, the electromagnetic wave from

the first oscillator should spread across the room at the speed of light and cause the second oscillator to respond—and indeed it did.

- B. In effect, Hertz had built a radio. On one side of the room was an antenna broadcasting a signal, and on the other side of the room was an antenna receiving the signal.
- C. Again, picture a moving electric charge at one point in space, which creates a ripple of electrical and magnetic fields that causes other charges, at another point in space, to move.

V. Maxwell's work opened up a new branch of physics—physical optics—that allowed scientists to think about optics in a new way.

- A. Instead of exploring the path of light rays through a prism or how a telescope might focus light, scientists could now think about the interaction of light (electromagnetic waves) with matter.
- B. Light had been studied since well before Newton; in fact, Newton's career as a physicist began with his experiments into the nature of color. He believed that light was "corpuscular," that is, made of particles, but the technology was not available to either prove or disprove this theory.
- C. In 1800, Thomas Young (1773–1829), conducted an experiment that convincingly proved that light is a wave phenomenon. For 60 years after Young, physicists wondered: If light is a wave, what material thing is "waving"? As we've said, Maxwell answered this question: Light is electrical and magnetic fields oscillating in empty space.

VI. Anything we want to know about light should, in principle, arise from Maxwell's equations, including its origin, propagation, and interactions with matter. We should be able to understand lenses, rainbows, prisms, diffraction, and many other phenomena.

- A. Maxwell's equations tell us that light carries energy. A moving electric charge is experiencing a force and, thus, accelerates over some distance; as we know, force multiplied by distance equals work, and work is a transfer of energy. Where does the energy go in this case? It spreads out in the electromagnetic wave.
- B. The speed at which this wave propagates, 186,000 miles per second, is independent of any details of the motion.
 - 1. Red light and blue light don't differ in their fundamental properties, but blue light has a higher oscillation frequency.
 - 2. An even higher oscillation frequency than that associated with blue light won't be perceived by the human brain; this is *ultraviolet radiation*. Still higher oscillation frequencies result in other kinds of electromagnetic radiation, such as X-rays or gamma rays.

3. A slower oscillation frequency than that associated with red light results in *infrared radiation*. This is another form of light, and we can build night-vision cameras that detect this form of radiation.
 4. In honor of Heinrich Hertz, we measure frequencies in units of cycles per second, now called *hertz*. The wall plug in your house is 60 Hz; your eye responds to about 1 million billion Hz.
 5. Beyond the infrared frequency is microwave radiation, and at a lower frequency still are radio waves.
- C. Maxwell left a legacy of the unification of electricity, magnetism, and light, and an explosion of new ideas and applications that took off from his four equations.

Essential Computer Sim:

Go to <http://phet.colorado.edu> and play with Radio Waves and Electromagnetic Fields; Microwaves and Blackbody Spectrum are both worth exploring, too.

Essential Reading:

Hewitt, chapter 25.

Hobson, chapter 9.

Recommended Reading:

Gonick, end of chapter 23 and chapter 24.

Questions to Consider:

1. Why is Maxwell's change (addition) to Ampère's law needed in order to result in electromagnetic waves?
2. Is sound an electromagnetic wave? Why or why not? What are the similarities? What are the differences?
3. Suppose you had goggles that allowed you to see infrared radiation in much the same way you currently see visible light. What would the room you are in "look like"? In particular, what would be bright and what would be dim?
4. When astronomers see a distant supernova from another galaxy, they see a sudden increase in brightness of all colors of the spectrum (as well as radio signal, X-ray signal, and any other part of the electromagnetic spectrum they might be able to measure), all at the same time. How is this evidence that the speed of light is independent of frequency?
5. The Sun emits most of its energy in the form of electromagnetic waves, and most of that energy is found only in the near visible spectrum (from red to violet), with a peak in energy flow around yellow. There is relatively little energy emitted in the infrared range (or beyond) or the ultraviolet range (or beyond). Our eyes, of course, are sensitive to just this same narrow band of frequencies that the Sun emits. Is this a remarkable coincidence, or can you think of a reason for it?

Lecture Nineteen

Vibrations and Waves

The wireless telegraph is not difficult to understand. The ordinary telegraph is like a very long cat. You pull the tail in New York, and it meows in Los Angeles. The wireless is the same, only without the cat.

—Albert Einstein

Scope: In this lecture, we step back from the story of electromagnetism to think about a very different kind of physics—the description and understanding of objects that vibrate and the associated phenomenon of waves. Vibrations and waves are *everywhere* in the natural world, and they provide a wonderful counterpoint to our usual language and model of particles. Understanding the big ideas of waves, especially the remarkable feature of *interference* and the point-counterpoint of waves versus particles, plays a key role in the developing story of physics.

Outline

- I. Vibrations and waves are everywhere in the physical world and provide a counterpoint to our usual language and model of particles.
 - A. Waves are a collective phenomenon, a way of seeing a simple pattern in complex situations. They have been studied since before Newton and were well known by Maxwell's time.
 - B. The “canonical” wave would be a pebble thrown into a pond, resulting in ripples of water spreading out. How can we *describe* this?
 1. The water itself is the medium for the wave. The water molecules are being displaced from their equilibrium point; as the wave passes, they move up and down. In other words, the ripples that we see on the pond arise from the displacement of particles from their normal equilibrium level.
 2. A wave is not a “thing” itself; it is a self-propagating disturbance. A classical wave has no obvious physical essence—no mass or clear position.
 3. If you look at the ocean, you see waves spread out parallel to the beach, one after another. This motion is not localized at all; the entire ocean carries gigantic, spread-out traveling waves.
- II. A subtle phenomenon takes place in the motion of a wave.
 - A. Picture a wave traveling from left to right. The water—the medium of the wave—is moving *only* up and down; it is not traveling sideways.
 - B. Water waves near the beach, where we most often see them, become nonlinear—the water splashes sideways—and the waves are no longer

ideal classical waves. If you were sitting in a dinghy beyond the break, however, you would see that the waves cause you to bob up and down on the water; they do not cause you to start surfing.

- C. Think of a field of wheat, disturbed by a rustling at one end. The wave spreads out and travels across the field, but no wheat stalk ever leaves its original spot. The wave travels across the field, but wheat does not!
- D. Consider the “wave” in a stadium, when people rise up and down in their seats in a sort of contagious motion. The wave rushes around the stadium, but the people (the medium) ultimately stay in their seats.

III. Waves may seem to behave in some respects like particles, but the two are not the same.

- A. Particles have mass and position and exist independent of any other material objects. None of these is a characteristic of waves.
- B. Let’s think about a Slinky[®] to visualize some of the differences between waves and particles.
 - 1. A Slinky stretched out motionless on the floor is the medium.
 - 2. Imagining holding one end of the Slinky fixed and jerking the other end up and down one time. A sideways pulse will travel from one end of the Slinky to the other.
 - 3. The pulse almost seems like a material object; it obviously travels from one end of the Slinky to the other and will even recoil and travel back. With this behavior, it’s easy to think that the pulse is somehow like a particle.
- C. Waves are characterized by a frequency (measured in Hz), a wavelength (the distance from one peak of a wave to the next), and a velocity (the speed of the wave itself, not the medium).
 - 1. The speed of the wave arises from interactions of the medium. Generally speaking, the more tightly coupled the “pieces” of the medium are, the faster the wave will ripple.
 - 2. If you jerk one end of a Slinky quickly (rapid frequency), the pulse will have a different shape (wavelength), but the pulse’s progress as a traveling wave will not be affected. (See the Essential Computer Sim at the end of this lecture.)
 - 3. If you stand up and sit down quickly in the stadium, you will affect how wide the stadium wave appears, but the traveling speed of the wave has to do with the interaction of you and the person in the seat next to you, not with your behavior alone.
 - 4. Maxwell saw this clearly with electromagnetic waves, which always travel at the speed of light.

IV. Waves are closely related to *simple harmonic motion (SHM)*—oscillations.

- A. The mathematics of SHM is described by the *sine wave*, which represents something moving back and forth smoothly, forever.

- B. SHM is ideal oscillatory motion. Do real objects in the world behave in this ideal way? To a large degree, the answer is yes. Electromagnetic waves are truly ideal; the Slinky and water waves away from the beach are fairly close approximations of SHM.
- C. What makes such motion, and why is it so common?
 - 1. Any material object that has a “home,” an equilibrium point, is pulled back to that point whenever it is displaced. The result is generally SHM.
 - 2. Think of a guitar string that you pull away from equilibrium, creating tension in the string. As the string is pulled backed toward its original position, the principle of inertia takes over (an object in motion remains in motion), and the string moves past its equilibrium point. Then, of course, it’s pulled back toward its original position again and so on.
 - 3. SHM takes place throughout the universe, for example, in the Earth orbiting the Sun (viewed from the side) or atoms moving in a crystal.
- D. How do we know when a wave is happening?
 - 1. If we zoom in on a wave, we see the SHM of the medium.
 - 2. If we zoom out, we see a wave traveling at some speed, and we no longer pay attention to the medium. We don’t see the SHM; in fact, any point on the crest of the wave seems to move in a straight line, like a particle.
- V. A defining characteristic of a wave is what happens when two waves come together.
 - A. Picture the Slinky again, with a person holding each end. If each person creates a pulse and two waves begin to travel along the Slinky from opposite directions, what happens when they meet?
 - B. If the waves were particles, they might break or bounce off each other, but in fact, the waves pass right through each other.
 - C. The most interesting phenomenon takes place at the point of intersection of the two waves; this is called *superposition* or *interference*.
 - 1. If I send a 1 cm tall “up pulse” along a Slinky and you send an “up pulse” from the other direction that is also 1 cm tall, at the point where they meet, we momentarily have a pulse that is 2 cm tall.
 - 2. If I send an “up pulse” and you send a “down pulse” from opposite ends of the Slinky, at the point where they meet, we momentarily get complete cancellation.
 - 3. *Constructive interference* takes place when two pulses add up, *destructive interference* is when they cancel each other out.
 - 4. Think about how dramatic destructive interference is: We would never have two particles coming together, briefly disappearing

from the universe when they meet, then reappearing after their interaction.

- VI.** No matter where we look in nature, we see oscillatory motion—the behavior of waves. Next we'll talk about some more specific examples of waves.

Essential Computer Sim:

Go to <http://phet.colorado.edu> and play with Wave on a String. You can use this sim to help answer several of the questions below. With this sim, you can also explore reflections, pulses, and the relationship between wavelength and frequency and learn about what affects wave speed. Also try Masses and Springs to learn about simple harmonic motion. Sound is a good simulation to get a sense of the propagation of waves and the geometry of interference in two dimensions. Going a little further afield, you can investigate the mathematics of sine waves with Fourier: Making Waves.

Essential Reading:

Hewitt, chapter 18.

Thinkwell, “10: Oscillatory Motion” (first segment on simple harmonic motion) and “11: Waves: The Basics of Waves.”

Recommended Reading:

Crease, chapter 4 and start of chapter 6.

Questions to Consider:

1. If you stretch a Slinky and wiggle one end, a pulse or wave will travel along the Slinky. What must you do to change the traveling speed of this wave? What is it about the wave that changes if you wiggle your hand faster? (The answer might surprise you. Give it a try. If you can't find a Slinky, go to the Wave on a String simulation and see if that helps you answer the question.)
2. Can you devise a real or simulated experiment to convince yourself that two pulses traveling oppositely on a Slinky combine to make a doubly big pulse? What happens if the two pulses are not the exact same shape?
3. How many examples of oscillations can you think of in everyday life? Are they all pure SHM, or are some oscillations more complicated? (Is the motion of a piston in your car engine SHM?)
4. Can two traveling waves, moving in opposite directions, reflect off of each other? Why or why not?
5. If two waves head toward one another with opposite “signs,” they destructively interfere at the point of intersection. Does this mean that some energy was temporarily destroyed, only to reappear later (when the waves continue along)? If not, where did the energy go at that special point?

Lecture Twenty

Sound Waves and Light Waves

Interference in ordinary language usually suggests opposition or hindrance, but in physics we often do not use language the way it was originally designed!

—Richard Feynman, from *The Feynman Lectures in Physics*, vol. I

Scope: What do physicists mean when they say that sound is a wave or light is a wave? In this lecture, we will consider this question. Newton (of course!) was one of the founders of modern optics. Although he conceived of light as a stream of particles, his classic and beautiful experiments with prisms and optical lenses led to both theoretical and practical understanding of light that lasted for a century. More than 100 years after Newton, Young turned the world of optics on its head when he convincingly and dramatically demonstrated that light was *not* made of particles but was, in fact, a wave phenomenon. Maxwell's theoretical triumph 50 years later, showing light to be an electromagnetic wave, tied the story off neatly. Showing that Newton was wrong about *anything* is inevitably "revolutionary" but in a very different way than Newton's "revolution" from Greek natural philosophy; Young's revolution altered and deepened our conceptions of physical phenomena without breaking the structure of physics itself.

Outline

- I. What do we mean when we say that sound is a wave?
 - A. Consider first a model for sound waves propagating in a medium, in this case, air.
 1. Think of air as a collection of tiny, independent particles, like superballs, flying around the room and bumping into one another and the walls.
 2. If you clap, you compress these superballs locally, creating a region of high pressure. The superballs will push against their neighbors, which in turn, extends the high-pressure region. The result is a traveling wave of compression, a disturbance of the pressure of the air itself.
 - B. The alternative to this wave model of sound might be one in which clapping results in the release of some kind of particles of sound.
- II. What experiments could we do to determine which model of sound—the particle model or the wave model—is more accurate?
 - A. We might, for example, try to measure the speed of sound, but doing so would not allow us to conclude whether we were dealing with particles or waves.

- B. At an outdoor concert, you might notice that even though you are some distance from the musicians, you still hear low frequencies and high frequencies at the same time.
1. This suggests that sound is a wave because, as we learned in the last lecture, both high- and low-frequency waves travel at the same speed.
 2. If sound had a particle nature, we might think that high-frequency sounds would correspond to higher energies, which would mean that these particles would travel at higher speeds.
 3. This argument is compelling, but not completely convincing, for determining which model is correct.
- C. Waves should be “wavy”; that is, if sound is a wave, it should, for instance, bend around corners, and in fact, it does. You can easily hear someone in another room even if the room is around a corner from where you are. Still, sound might be particles bouncing out of the room, through the doorway, and around the corner.
- D. To test our model, we might set up an experiment with a microphone, which is nothing more than a little flap of material that moves with the alternating high pressure and low pressure of sound waves. The microphone converts the motion of this little flap into a voltage.
1. We could watch the output of the microphone on an oscilloscope, and we would see the beautiful sine wave pattern that we talked about in Lecture Nineteen.
 2. Is this proof that sound is a wave? Not completely, because sound particles might be striking the flap, which then “rings” like a bell.
- E. As mentioned in the last lecture, the most distinctive feature of waves is the characteristic of interference. How could you observe this characteristic with sound waves?
1. You might set up two speakers, one in front of you on the left and one in front of you on the right. You stand at a point equally distant from both speakers while they both broadcast the same steady tone with the exact same loudness and pitch. At low frequencies, you can actually see the cone of the speaker moving in and out, but this is still not proof that we’re dealing with waves.
 2. You might then reverse the wires on one speaker so that when one speaker is pushing out, the other is pulling in; the speakers would be precisely out of synch, or *out of phase*.
 3. In the wave model, when a speaker is pushing out, it’s creating high pressure, and when it’s pulling in, it’s creating low pressure. Because the sound waves started out of phase and travel an equal distance to you, they will still be out of phase, and they will destructively interfere at all times. You should hear nothing.

4. In the particle model, the speakers spew out sound particles, whether they are in phase or not. The sound you hear, then, should be twice as loud.
 5. Amazingly, if you performed this experiment (which is a little tricky), you would find that you could be standing in a room with two speakers broadcasting and hear silence. Audiophiles take this effect into account when setting up speakers in their homes.
- F. We can also think of another experiment that might decide the question of whether sound has a wave nature or a particle nature: What if we remove the medium in which sound propagates (air)?
1. If sound is a pressure wave in air, then without air, there can be no wave. But if sound is made up of particles, the particles should still be able to travel through a vacuum.
 2. This experiment was performed in the 1600s. Today, we could put a bell inside a jar and pump out all the air. As the air is removed, we could see the clapper of the bell moving, but we wouldn't be able to hear any ringing.
- G. No single experiment proves the hypothesis that sound is a wave, but we have seen that sound is not particles. The wave model seems to be consistent, and it enables us to make predictions about what will happen in our experiments.

III. It is more difficult to conceive of light as a wave.

- A. This difficulty stems from the fact that the wavelength of light is very small, less than a micrometer. In contrast, the wavelength of sound is on a more human scale and is noticeable, as we saw when we talked about the room with two out-of-sync speakers.
- B. Newton believed that light was made up of light particles, which is not a completely illogical hypothesis. Recall that sound can bend around a corner; you can hear a person in another room around a corner from where you are. But you can't see a person in another room unless that room is directly in front of you. This seems to be evidence that light is not a wave. (We now know that the smaller the wavelength, the less waves tend to bend around corners.)
- C. In 1801, Thomas Young conducted a dramatic experiment in which he managed to see two light waves canceling each other out, much as we saw with sound waves in our speaker example.
1. Young used a bright light source, with the light passing through a partition into which he had cut a narrow slit. As the light passed through this slit, it spread out in all directions and illuminated the far wall uniformly. This setup is the equivalent of creating a point-like source of light.
 2. Next, Young cut two slits in the far wall (this is the *double-slit experiment*). The expanding waves of light striking those two slits

are symmetrical. Thus, the light at the two slits would be in phase (*coherent*).

3. Two expanding waves of light now travel through the back side of the double-slit partition, and there are now places further along in the room where they add up and other places where they cancel.
 4. The result is a classic interference pattern—alternating bright and dark spots in a pattern exactly predictable from the wave model. Further, we can predict what would happen if we changed the color of the light, the number of slits, or the spacing of the slits.
- D. Young's experiment clearly proved that light is a wave, because only waves exhibit this kind of "destructive interference." But a puzzle remained: What is "waving"? As we've discussed, Maxwell solved this puzzle 50 years later with the idea that light is an electromagnetic wave—that is, electromagnetic fields waving in strength.
- E. As we've seen with other fundamental ideas of physics, once we know that light and sound are waves, we can begin to find practical applications for this knowledge, such as sound-canceling headphones and anti-reflective coatings on glass.

Essential Computer Sim:

Go to <http://phet.colorado.edu> and play with Sound (particularly the Two Source Interference and Varying Air Pressure tabs, both of which will help you with the questions below); also try Quantum Wave Interference.

Essential Reading:

Hewitt, chapters 19 and 28.

Hobson, start of chapter 8

Thinkwell, "11: Waves: Waves on Top of Waves," "11: Sound," and "11: Interference."

Recommended Reading:

Crease, chapters 4 and 6.

Questions to Consider:

1. If you know that energy is being transmitted from one place to another, what sort of experiments can you think of to determine whether the energy was being carried by particles (material bodies) or by waves?
2. Give two reasons why sound waves decrease in strength as they move away from the source. How would this compare to electromagnetic waves leaving a source in empty space, and how would *that* compare to electromagnetic waves leaving a source in a region containing material (such as gases or glass)?

3. If you have a computer with a sound card, go to the Sound simulation at <http://phet.colorado.edu> and look at the tab for Two Source Interference. The listener starts at the exact midpoint. Do the two sound waves add up or cancel out? Move the listener around. Can you find the quiet spots where destructive interference is taking place? What can you say about the location of those spots? (How does the location depend on the frequency of sound?) Can you explain what is going on with the physical air (and air pressure) at those quiet spots?
4. Go to the Quantum Wave Interference simulation Start with photons, and turn the intensity and screen brightness up high. Choose Double Slits; make the slit width as small as possible and make the slit separation as wide as possible, with the vertical position in the middle somewhere (so that you're basically doing Young's experiment!) If you believed that light was a stream of particles, and you shined light from a pinpoint through *two* holes, what pattern of light would you expect to see on a far wall? Where would it be bright, and where would it get darker? Is there any reason to expect the light to be bright at a spot *directly behind the wall* at the center, that is, exactly between the two slits? Shouldn't that be a dark shadow? How does the wave nature of light explain the brightness right there at the midpoint?

Lecture Twenty-One

The Atomic Hypothesis

If, in some cataclysm, all scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or atomic fact, or whatever you wish to call it) that all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence you will see an enormous amount of information about the world, if just a little imagination and thinking are applied.

—Richard Feynman, from the *Feynman Lectures in Physics*, vol. I

Scope: In the first part of this course, we looked at fundamental, underlying principles of physics, explored particular forces, and saw that electricity and magnetism were unified and that the resulting force—electromagnetism—helps us to understand light and light waves. There's one more important part of the story—the idea that the world is made of atoms, independent, fundamental building blocks of matter. We'll trace this idea's long and complex history, which offers a unifying principle greater than Maxwell's equations. Energy, the structure of materials, chemistry, heat, optics, and more become tied together and often relatively simple to describe and explain at a fundamental level, once we have a basic understanding of atoms.

Outline

- I. Greek natural philosophers debated what the world is made of.
 - A. In about 400 B.C., Democritus (c. 470–380 B.C.E.) promoted a fairly modern idea of atoms: that at a fundamental level, the world is made of “uncuttable” (*atomos*) objects.
 - B. Aristotle (384–322 B.C.E.) disagreed; his worldview encompassed qualities, which would be infinitely divisible.
 - C. At the time, this was a philosophical, not a scientific, debate; people didn't consider measurable consequences of one idea versus the other.
 1. A stick of butter is a material that has certain defining characteristics: it's yellow, it melts at room temperature, and so on. If I cut the stick of butter in half, it's still butter; I haven't changed the essential character of it. I could continue this process of cutting the butter in half, and all along, I would still have butter.

- 2. Democritus argued that at some point, I would reach an extremely tiny piece of butter that I could no longer cut. As we said, Aristotle disagreed with this idea. (For him, it's "butter all the way")

D. To decide this question, we must consider the consequences of both theories.

II. Atoms are observable with modern equipment, such as a scanning electron microscope. Even in the 1700s, however, people were becoming convinced that the idea of atoms was a useful and correct description of nature.

- A. An atomic worldview is quite consistent with the classical physics ideas of reductionism and determinism, yet it also forms a bridge to modern ideas. In fact, I would argue that the classical physics story ends with the atomic theory; modern physics then takes over, looking at what the atom itself is made of. Even without the atomic worldview, much of classical physics still "works."
- B. According to the atomic hypothesis, there are about 100 different kinds of atoms, such as carbon, nitrogen, oxygen, hydrogen, and so on, that combine to form all material objects—solids, liquids, and gases.
- C. If we know the mass of the atoms and their interactions with other atoms, we can build (and understand) any material substance.

III. The idea of atoms helps us make sense of both physics and chemistry.

- A. In Newton's era, alchemy served as a sort of proto-chemistry. Alchemy involved experimentation with materials, but it was practiced in secret and had a mystical aura.
- B. Antoine Lavoisier (1743–1794), a French chemist working at the end of the 18th century, took the first classically scientific steps in chemistry. He showed, for example, that mass is conserved in chemical reactions, which tended to confirm the atomic hypothesis.
- C. John Dalton (1766–1844), a British chemist working soon after Lavoisier, is called the father of the atomic model. He carefully studied many aspects of chemistry. Let's look at one example: forming water.
 - 1. Mixing 2 parts (by mass) of hydrogen with 16 parts (by mass) of oxygen yields 18 parts of water vapor.
 - 2. Looking instead at volumes, the combining ratios are 2 volume elements of hydrogen and 1 volume element of oxygen to yield 1 volume of water vapor. This makes sense if water is H_2O , that is, if a water molecule has 2 parts hydrogen for every 1 part oxygen.
- D. In the end, the atomic model is a simple and elegant system that allows us to organize the elements and make sense of their properties.

IV. The experimental and theoretical work of Robert Boyle (1627–1691) in the late 1600s, Jacques Charles (1746–1823) in the late 1700s, and Amedeo Avogadro (1776–1856) in the early 1800s followed a parallel path toward

the atomic hypothesis, this time, from the perspective of physics.

- A. Instead of combining elements and looking at ratios and masses, these investigators were doing physics, that is, measuring forces, pressure, temperature, and so on. They found that the atomic hypothesis of chemistry helped them make sense of the physical properties of gases.
- B. All gases have some universal characteristics. For example, they obey the *universal gas law*, or *ideal gas law*, which involves a relationship of pressure, volume, and temperature.
- C. The atomic hypothesis characterizes a gas as a collection of atoms, independent “superballs” flying around in space. Pressure, then, results from these objects bouncing off the walls. This is an extension of the atomic hypothesis, a branch of physics called *statistical mechanics* (used in the explanation of atomic systems).

V. The atomic model leads us to much deeper questions about nature.

- A. What makes a solid substance melt? The atoms in a solid state are bound together by chemical forces. As the substance is heated, the atoms gain kinetic energy; when the energy reaches a certain point, the chemical bond is broken and the atoms are free to move around. The result is a liquid, but note that in a liquid, the atoms are still in contact with one another. If the substance is heated still more, the atoms reach an energy level at which they lose contact, becoming a gas.
- B. What makes a substance dissolve? Sugar stirred into water seems to disappear—where did it go? The atoms making up the sugar migrate into the spaces between the water molecules.
- C. These are qualitative questions about atoms, but we might also begin to ask quantitative questions. For example, how big are atoms?
 - 1. To answer this question, Benjamin Franklin conducted an experiment in which he placed a drop of oil onto a pond. By equating the volume of the drop to the volume of the resulting oil slick, Franklin came up with an estimate of the height of the slick, very roughly 1 atomic diameter, about a billionth of a meter.
 - 2. The size of an atom can also be measured by a technique called *X-ray interference* and is comparable to the wavelength of X-rays.
- D. The atomic hypothesis also helps us understand temperature (a measure of the energy of atoms). We'll explore this idea in the next lecture.

VI. Atoms are somewhat abstract to us because no one has ever seen one and no one ever will (they are much, much smaller than the visible wavelength of light). By now, however, atoms are a well-established idea in physics. We can see the consequences of the atomic worldview all around us, enabling us to explain and calculate the properties of ordinary objects.

Essential Computer Sim:

Go to <http://phet.colorado.edu> and play with Gas Properties to study the ideal gas law and get a visual sense for how the atomic model is directly responsible for the observables, such as temperature and pressure. Balloons and Buoyancy may help you understand *why* a hot air balloon rises, based on the atomic model. For further investigation, check out any of the sims in the Chemistry category.

Essential Reading:

Hewitt, chapter 10.

Hobson, chapter 2.

March, chapter 13.

Recommended Reading:

Cropper, chapter 13.

Feynman Lectures, introductory chapter on atoms.

Questions to Consider:

1. What does the atomic hypothesis predict will happen to gas pressure as you increase its temperature? (Temperature measures the average kinetic energy of atoms, and pressure is related to the force the atoms apply to the walls. If you increase energy, what happens to the force atoms apply to the walls? What happens to the frequency at which atoms bounce off the walls?)
2. Which has more atoms, 1 kg of nitrogen gas or 1 kg of hydrogen gas? (Note: Hydrogen atoms are the lightest possible atoms. Nitrogen atoms are 14 times heavier than hydrogen.) Which has more atoms, 1 liter of nitrogen gas or 1 liter of hydrogen gas? (A liter is a measure of volume, not mass.)
3. Copper atoms have a mass of 63 *atomic mass units* (each *amu* is 1.66×10^{-27} grams). Estimate the mass of a penny. (A stamp scale can help. Otherwise, can you think of a way of comparing an unknown mass to known masses, for example, with a pile of pennies?) From that, estimate the number of atoms in a penny. Now estimate the volume of a penny (if you don't have a ruler to measure something as small in thickness as a penny, could you come up with a trick by stacking pennies to make an estimate?) Given the total volume and your estimate of the number of atoms, what is the volume of one atom? Assuming that the atom is a little "cube," what is the size of the atom? (Your answer should come out to be around 10^{-9} meters on a side.) If you look at a periodic table (go to the Web!), you can find atomic masses of all elements. Make a similar estimate for other materials you find in your house. Is the size of all atoms about the same?
4. Thinking more about the previous question. How could you figure out the mass of a single copper atom (without looking it up in the periodic table)? In other words, how did people figure out the mass numbers in that table?

Lecture Twenty-Two

Energy in Systems—Heat and Thermodynamics

Thermodynamics is the only physical theory of universal content which, within the framework of the applicability of its basic concepts, I am convinced will never be overthrown.

—Albert Einstein.

Scope: So far in these lectures, we've tried to simplify as much and as often as possible, before adding complexity back in by degree. Historically, this strategy has been extremely productive in physics and continues to be used to this day. In this lecture and the remaining ones in the course, we'll make the transition from simplicity to the recognition that the world is constructed of atoms, and thus, even simple things may be enormously complicated. We'll look at the field of thermodynamics, the study of heat and temperature, which requires an understanding of microscopic internal degrees of freedom exhibited by atoms. The physics of thermodynamics is everywhere—we use it in heating and cooling our homes, cooking food, taking the temperature of a child with a fever, and predicting the melting of glaciers. Thermodynamics is an appropriate ending topic for this course because it pulls together all the “big ideas” of classical physics, including Newton's force laws, energy principles, the atomic hypothesis, and statistical mechanics.

Outline

- I. Thermodynamics begins with a focus on energy flow using the principles of statistical mechanics (which amounts to “averaging over atoms”).
 - A. Complex, real-life systems involve astronomical numbers of particles. A pot of boiling water might contain a million billion billion molecules.
 - B. The reductionist viewpoint tells us to focus in on individual particles and track their reactions with regard to Newton's laws. This would be a hopeless task (given such a large number of particles to track).
 - C. Instead, statistical mechanics tells us to think about averages—the behavior of *typical* atoms—without worrying about the details. This simplifies the story enormously.
 - D. Insurance companies use this principle when they make predictions about when people will marry, have children, or die. It's not possible to make such predictions about individuals, but it is possible to do so for a large pool of people.
 - E. Because atoms are simpler than people, predictions about average quantities are all the more reliable.

- II.** Thermodynamics is characterized by three laws, plus a starting (*zeroth*) law. The zeroth and first laws, which we'll look at in this lecture, are about work and energy, along with energy flow. The second and third laws add a new concept that we'll talk about in the next lecture—*entropy*.
- III.** The history of thermodynamics dates back to antiquity.
- A.** Early ideas about heat included the *caloric theory*, in which heat was a material substance (a physical fluid) associated with high temperatures.
 - B.** The basis for the modern model of thermodynamics came from James Joule, whom we discussed in an earlier lecture. He articulated the idea that heat is the flow of thermal energy.
 - 1. Recall that energy comes in many forms—kinetic energy, gravitational potential energy, chemical potential energy, and so on.
 - 2. Think about a book sliding across a table. It starts with pure kinetic energy—energy of motion.
 - 3. When friction grinds the book to a halt, where did the energy go? It is not stored in an obvious way, as you might see in a compressed spring.
 - 4. With the atomic hypothesis, we know exactly what happened to the energy. The friction caused an increase in the motion of atoms in the book and table; thus, they have more kinetic energy. The thermal energy is stored in random kinetic energy of these atoms.
 - 5. Thermal energy is measured in joules, just like any other kind of energy; we could measure quantitatively the thermal energy of the book and the table.
 - C.** Experiments in thermodynamics were difficult to conduct, and progress in this field of physics was slow.
 - 1. These ideas might have been accessible to Newton, but it took almost 200 years to put the story together carefully.
 - 2. Part of the problem was that it's difficult to isolate a system thermally. It's also difficult to measure small temperature changes accurately, and older thermometers tended to interfere with scientific analysis.
 - D.** Many physicists worked for years to make a convincing case that thermal energy is, indeed, just another form of energy, not some mysterious caloric fluid.
 - 1. We can think of some simplistic arguments against the caloric theory. For example, if you have a cup of coffee that is heated by the "caloric," it should weigh less as it cools off and the caloric leaves it.
 - 2. Suppose you have a block of dense material, and you want to drill through it. You know what will happen: As the drill bit grinds away, it will get hot. But where is the caloric coming from in this

system? Is it created out of nothing by the interaction of two cool objects?

3. Ultimately, many experiments verified Joule's idea that heat was not a material substance but related directly to energy.

IV. The zeroth law of thermodynamics defines *thermal equilibrium*.

- A. Two objects in contact with each other may or may not be in thermal equilibrium. If they're not, they will change; one of them will cool off and one of them will warm up until nothing more happens. The two objects are then in thermal equilibrium.
- B. The zeroth law of thermodynamics says that if object A is in equilibrium with object B, and object B is in equilibrium with object C, then A is in equilibrium with C. This is a practical statement, allowing us to use thermometers reliably.
- C. Temperature becomes meaningful with the zeroth law of thermodynamics, and the law tells us that we measure temperature by comparison with a standard.
- D. Microscopically, the zeroth law also makes sense. Temperature measures the average kinetic energy of the atoms in a system. The atoms in my body have a certain average kinetic energy; when I take my temperature, the thermometer reaches thermal equilibrium with my body.
 1. If the thermometer starts off cooler than my body temperature, its atoms are moving more slowly.
 2. What happens if we bring two solid objects into contact, one of them with atoms moving slowly and one of them with atoms moving rapidly? The atoms that are moving rapidly will bump into the slow ones more frequently and speed them up. Of course, the atoms that were moving rapidly will also slow down in the process.
 3. In the end, in equilibrium, the *average* energy of all the atoms will be the same.
 4. Temperature has nothing to do with the material object involved; it is nothing more or less than the average kinetic energy of atoms.

V. The first law of thermodynamics is a statement of energy conservation for complex objects.

- A. To understand this idea, we need to define our vocabulary: *temperature*, *thermal energy*, and *heat*.
 1. *Temperature* is a measure of the average kinetic energy of particles.
 2. *Thermal energy* refers to the sum, not the average, of internal kinetic energies.

3. In physics, *heat* is used as a verb, not a noun. Heat is defined as the transfer of thermal energy from one object to another.
- B. The first law of thermodynamics says that energy is conserved.
 1. Total change in thermal energy arises from work plus heat.
 2. If you put a pot of water on a hot stove the water will get hotter. That means that the average energy of atoms is increasing; where is this energy coming from?
 3. A classic Newtonian concept is that energy is transferred through work. Thus, *stirring* the water would be one way of increasing its temperature
 4. In our scenario, though, we are transferring random motion of the atoms on the stovetop and converting that to random motion of atoms in the water. (So here, we increase the temperature of the water by heating, *rather* than by doing mechanical work.)
 5. Joule argued that heat and mechanical work are equivalent; they can both be measured in the same way. In fact, he measured the *mechanical equivalent of heat*.
- C. The bottom line so far is that objects can hold thermal energy (hidden, *internal energy*), but this energy is fundamentally no different than any other kind. Up to this point, thermodynamics is a bookkeeping tool that allows us to keep track of energy. In the next lecture, we'll talk about the entropy concept, which will take us beyond bookkeeping.

Essential Computer Sim:

Go to <http://phet.colorado.edu> and play with Gas Properties again. Click on the Energy Histograms box and see if you can make sense of the resulting graphs!

Essential Reading:

Hewitt, first half of chapter 17.

Hobson, start of chapter 7.

Recommended Reading:

Hewitt, chapters 13–16.

Cropper, chapters 6–8.

Questions to Consider:

1. A metal and a wooden object sit in the same room for a long time. Which one has the higher temperature, or are they the same? Why? In which one do the atoms have a higher average kinetic energy, or are they the same? Why? Now touch them; the metal one will *feel* cooler. Can you make sense of this, given your (probably correct) answer to the previous question?
2. What happens to the work done when you vigorously shake the orange juice you're mixing up?

3. When you put an ice cube in hot water, does temperature “flow” between the ice and the water? (If not, what does flow between them?)
4. Does a ceiling fan cool the air in a room? If not, why do you use one? What is it doing?
5. Use the principle of conservation of energy to explain why the temperature of the air in a bike pump increases when you compress it, but the temperature of compressed gas in a can decreases when you let the gas suddenly expand.
6. Can you convert internal (thermal) energy into useful (mechanical, kinetic) energy? If so, give some examples.
7. Use the first law of thermodynamics to explain why the total energy of an *isolated* system never changes. Does that mean that “nothing interesting” can ever happen to an isolated system?

Lecture Twenty-Three

Heat and the Second Law of Thermodynamics

The law that entropy always increases—the second law of thermodynamics—holds, I think, the supreme position among the laws of physics. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations—then so much the worse for Maxwell's equations. If it is found to be contradicted by observation—well, these experimentalists do bungle things from time to time. But if your theory is found to be against the Second Law of Thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.

— Sir Arthur Eddington.

The Laws of Thermodynamics:

First Law: You can't win.

Second Law: You can't break even.

Third Law: You can't get out of the game.

— A popular (and fairly accurate) scientific joke

Scope: Thermodynamics began as an application and extension of the basic idea of energy conservation, and the first law of thermodynamics is a mathematical statement about conservation of energy. The most significant application of thermodynamics in our lives is a *heat engine*. This is a generic term for a device or system that converts thermal energy into useful work. In order to discuss heat engines, we will need to look at the concept of *entropy*, an abstract, elegant, and powerful property of systems. Entropy can be defined in several ways, related to heat flow and temperature or to “randomness.” The implications arising from entropy considerations are profound and practical, expressed colloquially as “You can’t win, you can’t break even, and you can’t get out of the game.” Entropy and the laws of thermodynamics help us understand why heat engines are limited in efficiency (and why perpetual motion machines are impossible), despite all the creativity and best efforts of engineers and inventors. These principles describe the natural tendency of isolated systems toward states of more disorder and even touch on the direction of the “arrow of time.”

Outline

- I. Let's begin by exploring some of the broad properties of heat engines.
 - A. A heat engine has a working material, a hot reservoir to take in thermal energy, and a cold reservoir to release thermal energy. The working material (for example, gas) converts thermal energy from the hot reservoir into mechanical energy. An example would be a car engine.

- B. A heat engine can also extract thermal energy from a cold reservoir and exhaust it to a hot reservoir. An example of this would be an air conditioner or refrigerator.
- II. By the 1800s, people were using the principles of heat engines to build steam engines, but the engines exhibited poor efficiency.
- A. We can define *efficiency* as “what you get” divided by “what you pay for.” For an engine, “what you get” is the amount of mechanical energy provided by the device; “what you pay for” is the amount of energy put into the device, measured as chemical potential energy.
- B. With conservation of energy, we know that “what you get” can never be greater than “what you pay for.” In other words, according to the first law of thermodynamics, the efficiency of a heat engine can never exceed 1.
- C. In practice, if you put 1000 joules of stored chemical energy into a car in the form of gasoline, you might get 200 joules of useful work (kinetic energy) out of the system, for an efficiency of 20%. The remaining 800 joules is in the form of exhaust heat, a thermal energy increase of the cold reservoir (which in this case is the atmosphere.)
- III. The second law of thermodynamics tells us that the maximum efficiency of a heat engine is generally much less than 100%.
- A. This law was discovered by Sadi Carnot (1796–1832), a French engineer working with steam engines around 1800. Carnot was able to think about the fundamental principles governing steam engines, looking beyond the details of what fuel was used or what materials the engines were made of.
- B. Carnot recognized the simple fact that, in an isolated system, hot objects always spontaneously cool down and cold objects always spontaneously warm up until they reach equilibrium.
- C. Why does this principle never work in reverse? With two objects, why doesn't the hot one get hotter and the cold one get colder? Such a phenomenon could still conserve energy: The total thermal energy of the hot object would increase, but the total thermal energy of the cold object would decrease. The fact that this doesn't spontaneously happen is the second law of thermodynamics.
- D. Carnot recognized that the second law had many concrete consequences.
1. The maximum efficiency of a heat engine is determined by the temperatures of the hot and cold reservoirs.
 2. For a steam engine operating with fuel (boiling water) at 100° C and exhausting to room-temperature air, the maximum possible efficiency is a depressing 20%.

3. This is a fundamental law of physics, and no heat engine, no matter how well engineered, can beat this limit.

E. The statistical mechanical view, which we'll discuss in a few moments, helps us see this law even more clearly; the second law arises from how atoms move and rearrange themselves, and there is no way around it.

IV. The second law of thermodynamics can be stated in many different ways. The concept of *entropy* is a way of reframing the second law.

A. Entropy is a measurable quantity of systems, much as energy is. The statistical mechanical worldview teaches us to think about entropy microscopically as a measure of randomness. The more orderly a system is, the less entropy it has and vice versa.

B. What do we mean by *randomness*? Microscopically, the term refers to how many "states" are available in a system.

C. Adding energy is one way of increasing entropy, but the two are not the same properties.

D. The second law of thermodynamics is a counting argument, based on pure probability.

1. If you buy a new deck of cards, it is highly ordered (low entropy). When you shuffle the deck a number of times, the cards will become more random (increasing entropy), but you will never, in your lifetime, shuffle the deck back into its original ordered state.

2. With 52 cards, there is an absurdly tiny chance that the cards could be shuffled back into order, but with a million billion billion atoms in a pot of water, the chance of entropy spontaneously decreasing through natural events is 0 to any degree of approximation!

E. We can see this in relation to Carnot's statement of the second law of thermodynamics.

1. In isolated thermal systems, hotter objects get cooler and cooler objects get hotter.

2. If we're thinking about entropy, the cooler object could not become even colder, because that would be an increase in entropy. (Colder objects tend to be more orderly.)

V. Once we think about thermodynamics in this way, that is, with regard to systems and their natural evolution, we realize that some forms of energy are more *useful* than others.

A. More useful energy has less entropy. Every molecule in a car traveling down the highway is going in the same direction with the same average speed. This system is about as orderly as we can imagine, and the state is one of very low entropy for that amount of energy to be configured in. If the car crashed, the energy would be conserved, but the thermal energy would be in a much more random state.

- B. This tells us why engines have a maximum efficiency. The hot gases in a car engine are in a state of random thermal energy. The engine extracts some of that energy to drive the car, but all of the energy cannot be transferred to motion of the car, because that would violate the second law of thermodynamics. Converting all the random thermal energy in the gas to kinetic energy of the car would decrease the overall entropy of the system.

VI. The second law of thermodynamics does not say that entropy never decreases. It says only that entropy of *isolated systems* never decreases.

- A. When you put water in the freezer, the water molecules spontaneously freeze, becoming ice. That's moving to a state of more order, or lower entropy, but it happens because the water is not isolated; freezing the water requires external energy.
- B. Some people have argued that human beings are low-entropy systems. "Making" a human involves increasing the order of certain chemicals to form organs; locally, then, entropy is decreasing. As a baby is formed, however, the mother requires energy from outside systems, and at the same time, she is increasing the entropy of the environment by releasing waste heat. Overall, entropy in the universe is increasing!

VII. All of this leads to a philosophical question about time: As time goes by, entropy is increasing, and we always think of time as going forward. The "arrow of time" points in only one direction.

- A. Newton's laws don't tell us why time should go one way and not the other. Watching a movie of billiard balls colliding on a table, we couldn't tell whether the movie was running forward or backward. Newton's laws are *time reversible*.
- B. But thermodynamic processes are not time reversible. If we watched a movie of an egg falling to the floor and breaking (and heating the floor slightly), we would know very well whether the movie was running forward or backward. We know that we could never use the thermal energy from the floor to repair the egg and sending it flying back upward into a person's waiting hands.
- C. It's possible, then, that the direction of time is associated with the second law of thermodynamics.

Essential Computer Sim:

Go to <http://phet.colorado.edu> and play with Friction and Reversible Reactions.

Essential Reading:

Hewitt, second half of chapter 17.

Hobson, rest of chapter 7.

Recommended Reading:

Cropper, chapters 3, 9–10.

Lightman, chapter 2.

Questions to Consider:

1. Explain how the laws of thermodynamics are, in a sense, equivalent to the joke lines quoted at the start of this lecture. (We didn't cover the third law, so just focus on the first two.)
2. Can you come up with several examples of naturally occurring processes that show how high-quality (usable) energy degrades into lower-quality (internal, thermal) energy?
3. When you clean up a room, what is happening to the entropy (randomness) of the room? Does this process violate the second law of thermodynamics?
4. Think about watching a movie of natural events, but you don't know if the movie is running forward or backward. Come up with some events where you could not tell which way the movie was running and others where it would be obvious. Now think about entropy—does it help explain the difference between these classes of events?
5. If a company claims it will produce a new super-efficient gasoline-powered engine that will put out 200 horsepower (hp) steadily for an hour on 1 gallon of gas, are you interested in buying the company's stock (or its product), or should you report the company to the Better Business Bureau as scammers? (Useful data: One gallon of gas contains 36.6 kWh of stored chemical energy, and 1 hp is 750 watts.)
6. If a company claims that it can rebuild your carburetor to make your car 90% efficient at converting gas energy into energy of motion, are you interested, or are they scamming you?

Lecture Twenty-Four

The Grand Picture of Classical Physics

Poets say science takes away from the beauty of the stars—mere globs of gas atoms. Nothing is “mere.” I too can see the stars on a desert night, and feel them. But do I see less or more? The vastness of the heavens stretches my imagination—stuck on this carousel my little eye can catch one-million-year-old light. A vast pattern—of which I am a part... What is the pattern or the meaning or the why? It does not do harm to the mystery to know a little more about it. For far more marvelous is the truth than any artists of the past imagined it. Why do the poets of the present not speak of it? What men are poets who can speak of Jupiter if he were a man, but if he is an immense spinning sphere of methane and ammonia must be silent?

—Richard Feynman, footnote in *The Feynman Lectures on Physics*

Before I came here I was confused about this subject. Having listened to your lecture I am still confused. But on a higher level.

—Fermi

Scope: Classical physics is defined in part, historically and, in part, by a philosophical mindset: The world is ordered, and there is a limited set of fundamental ideas that explain and predict all natural phenomena. The world is made of matter and energy, existing in space and time, with measurable properties and behaviors. These core ideas can be quantified via a small, consistent set of assumptions and mathematical relations, with enormous practical and predictive power. The specific ideas we have discussed form just part of what we mean by classical physics: force and acceleration as “cause and effect”; energy flow as an alternative tool for thinking about natural processes; gravity, electricity, and magnetism as fundamental forces; and matter made of atoms, with optics and thermodynamics as natural consequences. The universe in this framing is deterministic and “clock-like,” with complex behavior understood by a reductionist approach to first principles. This approach to scientific truth is still widely used by scientists and others working in many fields, but it is not the “end of understanding,” nor ultimate truth.

The developments of nuclear physics and radioactivity led to a totally new kind of mechanics, *quantum mechanics*, which approaches the world quite differently, with different assumptions about the “rules of the game,” as well as the philosophy behind the game. The ideas of relativity challenge Newton’s belief in a fixed, external space-time frame in which physics “occurs.” But all of these developments remain consistent with, or connect tightly to, classical physics, which will always remain as one of our grand intellectual achievements.

Outline

- I. Classical physics was firmly established by Isaac Newton and has undergone continuous development ever since.
 - A. We might define classical physics by its dates, starting in 1687 with the publication of the *Principia* and working our way up to about 1900. This definition isn't entirely satisfactory because classical physics continues to evolve to this day.
 - B. It's probably more productive to define classical physics in terms of its topics: mechanics of particles, forces of nature (gravity, electricity, magnetism), optics, thermodynamics, and so on. Classical physics also encompasses other topics, such as fluid flow or acoustics, that we haven't talked about in this course.
 - 1. These topics are often fundamentally about the world we live in—they apply to cars, bicycles, rockets, sports, architecture, and many other aspects of our lives.
 - 2. But classical physics also goes beyond everyday experience; with this study, we can understand particles down to a size of a billionth of a meter and up to the distance scales of our galaxy and beyond.
 - C. We might also define classical physics in terms of its applications. This discipline is still studied by all scientists, as well as architects, engineers, and others.
 - D. To paraphrase Newton, we could say that classical physics is the giant on whose shoulders science stands today.
- II. Classical physics is also, in part, a way of thinking about science, a scientific-philosophical vantage point.
 - A. A classical worldview is traditional and empirical: it says the world is real and exists independent of human beings; the goal of classical physics is to learn about this real world through experimentation and the development of coherent, unified theories.
 - B. A classical worldview is often reductionist, operating from the perspective that complex natural behavior can be described, explained, understood, and predicted by analyzing simpler components.
 - C. Related to the ideas that the world is real and reducible is the classical idea that the world is deterministic; that is, we can use our understanding of the world to make qualitative and quantitative predictions. In this view, our universe is similar to a giant clockwork.
 - D. Ultimately, classical physics postulates a small, cohesive set of underlying ideas. This set includes the kinematical ideas of position, velocity, and acceleration and the dynamical ideas of inertia, mass, force, momentum, and energy. It also includes some of the laws of nature that we discussed: Newton's laws, conservation laws (related to

energy, momentum, angular momentum, and charge), and Maxwell's equations.

- E. Finally, classical physics relies on the scientific method of investigation: observing the world, forming and testing hypotheses, and asking further questions.

III. Physics today has moved in new directions, to the realm of modern physics.

- A. Albert Einstein (1879–1955) is the “hero” of modern physics, although he was, in much of his work, a classical physicist too.
 - 1. Einstein's theory of special relativity built on Galilean relativity, the idea that the *laws* of nature are invariant, independent of the reference frame of the observer.
 - 2. Combining this idea with Maxwell's equations, Einstein realized a radical truth: The speed of light is itself a law of nature, independent of the observer.
 - 3. Einstein saw that neither Galileo nor Newton was completely wrong, but our intuitive understanding of space and time—the Newtonian idea that space and time were fixed and universal and independent of the observer—required revision. For example, relativity requires us to redefine momentum and kinetic energy, for objects traveling at speeds close to the speed of light.
 - 4. In the same way, Einstein's theory of general relativity changed the way we think about gravity. It re-imagines space and time in a geometrical sense and gives us a new idea about what gravity is and where it comes from.
- B. Beginning around 1900, the field of quantum physics began to delve deeper into the atomic hypothesis of classical physics.
 - 1. When physicists tried to understand the structure of atoms themselves, it became apparent that Newton's laws were insufficient to deal with distance scales of billionths of a meter or smaller.
 - 2. The theory of quantum mechanics was not just a “fix” of Newton's laws; it altered the fundamental premises of classical physics, including determinism.
 - 3. Classical physics assumes that if we understand enough about the world, we can make predictions about natural phenomena, such as the weather. With quantum mechanics, we find that many measurements, such as the time required for a particle to decay, are fundamentally uncertain and cannot be predicted.
- C. Do these new discoveries completely unseat classical physics? Absolutely not. Classical physics describes the world we live in as accurately today as it did in the 1600s when Newton was first making sense of it. Modern physics *builds* on the underlying ideas of classical physics, expanding their bounds of applicability.

III. Classical physics has been one of the most fruitful, productive, and powerful intellectual endeavors in the history of civilization.

- A. We study classical physics, not because we're interested in history, but because it still influences much of contemporary science and engineering.
- B. We can also use classical physics as a tool to understand the science behind political issues involving energy or the environment.
- C. As we close this course, I hope you will keep these ideas in mind and investigate them further in your everyday experiences.

Recommended Reading:

The world is your oyster.

Questions to Consider:

1. In what ways does physics connect to your personal life? Is your interest in physics intellectual, academic, practical, or some combination of these?
2. Modern physics has changed the philosophical outlook of scientists on many levels and challenges ideas as fundamental as the absolute nature of space, or the nature of atoms, or even Newton's laws. (For example, $F = ma$, force = mass \times acceleration, is not useful or even completely correct, if you consider electrons inside an atom or objects traveling near the speed of light.) Given that, what is the value in studying classical physics?
3. Do physicists still "do" any classical physics? (Who else uses classical physics?)
4. What steps do you need to take to continue to satisfy your interest and curiosity in physics and science?

Biographical Notes

A biographical list of “key contributors” to the development of classical physics is almost impossible to compile because the number of contributors is so large! Although famous physicists often get sole credit for their accomplishments, the great discoveries are inevitably part of a web of scientific progress. Truly significant contributions come from both brilliant and more mediocre scientists, not to mention support from graduate and sometimes undergraduate students, technicians, lab assistants, and so on. Most of the discoveries in physics have a complex lineage; historians could (and do) quibble about the attributions and origins of almost every idea in the field. Some ideas get “rediscovered” or further developed, then attributed to the scientist who somehow was better able to spread the word. What follows is an extraordinarily abbreviated list of some of the *most* famous names in the field. The large number left out is painful to this “biographer” (who is also admittedly not even remotely a historian of physics).

It is also worth noting that the physics described in this course is directly descended from the Western European tradition, and it may seem culturally insensitive not to mention discoveries made by Asian, Native American, African, or Arabic science. This arises from a combination of the shameful ignorance of the author of this text and the nature of contemporary Western science education, in which there is a direct pedigree and narrative that flows through the Western tradition. By no means should we discount the discoveries that were made on other continents, but the historical story that sits aside conventional (Western) introductory courses in physics is predominantly European in nature.

Greek Philosopher-Scientists (600 B.C.E.–A.D. 150)

Western philosophy, including *natural philosophy* (the philosophical precursor to science) traces its roots back to the Greeks. Because this course deals with the Western tradition of physics, we need to mention the beginnings, even if only in passing, because it was the growth away from the ideas of the Greeks that has largely defined physics as we now know it.

Aristotle (384–322 B.C.E.). Aristotle’s name is perhaps most important to modern science, not for the work he did, but as a symbol. Up until the 18th and early 19th centuries, the studies of philosophy and science were closely linked. Aristotle was the author of the philosophical and scientific system that was to dominate Western thought into the 17th century. Although he has a large body of work devoted to mathematics, philosophy, and zoology, the most pertinent of Aristotle’s works for our course is his view on the motion of physical bodies.

Aristotle maintained that the speed of an object is determined by the magnitude of the force pushing it: The greater the force, the faster the body will move. Although initially quite plausible (and correct in situations where viscous drag

dominates; indeed, this is one of the most common mistakes made by students in introductory physics courses!), this model breaks down when applied to astronomical bodies. It was the interpretation of the stars (first by Ptolemy, followed by Copernicus, Kepler, Galileo, and finally, Newton) that proved to form a more robust basis for the study of physical motion.

Aristarchus (310–230 B.C.E.). Aristarchus was a mathematician and astronomer who came from the same island as Pythagoras. Most of what survives of his work comes in the form of quotes from other writers of his era and a few indirect references. Still, he is often credited with being one of the initial proponents of a heliocentric model—one in which the Earth and other planets rotate about the Sun. The only surviving work of Aristarchus is *On the Sizes and Distances of the Sun and Moon*, which attempts to estimate the distances between the Earth, the Sun, and the Moon by cunning use of geometry.

Ptolemy (c. 85–165). Ptolemy was the proponent of the geocentric (Earth-centered) model of the solar system that was to prevail in Europe for 1400 years. Unlike those of most other classical authors, many of Ptolemy's works survived the trials of time and are available to us now in their original forms. Based on philosophical and scientific ideas, Ptolemy's model proposed that the Sun and all the planets rotated about the Earth, each having a complex system of "gears" (epicycles) that rotated at the same time in order to account for the motion that the planets exhibit in the nighttime sky. (The word *planet* is derived from the Greek word for "wanderer.") The Ptolemaic model of the solar system is impressively accurate, satisfying observational astronomy's needs until the "modern" high-precision observations of the late 16th and early 17th centuries.

The Birth of Classical Physics (1500–1800)

Nicolaus Copernicus (1473–1543). Copernicus was born in Poland, the son of a copper merchant. When Nicolaus was 10, his father died, and he and his siblings were placed in the custody of their uncle, a Church canon. Nicolaus was educated at the cathedral school, then enrolled in the University of Krakow, where he received an education in Latin, philosophy, mathematics, and (most importantly) astronomy. He became a canon, like his uncle, and continued his education throughout his life, adding Greek, medicine, and canon law to his list of accomplishments.

Copernicus is given credit for one of the first proposals of a Sun-centered universe since the classical age. He first proposed his ideas in a small handwritten book in 1514 that he circulated anonymously amongst his friends. Meanwhile, his other duties included advising the pope on calendar reform, organizing the defense of his hometown, and carrying out currency reform. It wasn't until the end of his life, in 1543, that he published his final theory of the heliocentric universe. His magnum opus was deliberately circumspect, presenting itself as a theory rather than the absolute truth and, thus, avoiding

controversy and Church censorship. Although the details were still wrong (Copernicus assumed perfectly circular orbits for the planets), Galileo, Brahe, and Kepler all read this work and were profoundly influenced by it.

Tycho Brahe (1546–1601). Tycho Brahe was born into the Danish nobility; both his father and mother came from important families that were influential with the Danish king. At the age of 13, he began attending the University of Copenhagen, ostensibly to study law, but he soon discovered that his real passion was astronomy (helped along by an eclipse in 1560). As part of his studies, Brahe traveled on the Continent. In 1567, he was involved in an altercation with another Danish student while he was in Germany that resulted in part of his nose being cut off in a duel.

By the 1570s, Brahe had earned a reputation as Denmark's preeminent scientist. When he announced his intention to leave Denmark, the king offered him an island on which to build a royal observatory as enticement to stay. This observatory at Hven collected data on the position of stars in the sky to an unmatched degree of precision (without the use of telescopes, which were not yet in use for astronomical observations!). Brahe would pass on these data to Kepler, leading to Kepler's three laws of celestial motion. In 1588, the king who had appointed Brahe died, and Brahe was not in favor with the new monarch. He left his position in 1597 for Germany, where he was appointed imperial mathematician in 1599.

Brahe died at the age of 65. The (possibly apocryphal) story is that he died from a ruptured bladder, caused by his refusal to leave the table at a feast before his host did.

Johannes Kepler (1571–1630). Kepler was the son of a mercenary soldier and an innkeeper's daughter in what is now modern Germany. His father died in a war in the Netherlands when Johannes was 5 years old. The boy was schooled by monks and, throughout his life, was profoundly religious, seeing his work as part of the Christian duty to understand the works of God.

The contribution for which Kepler is most remembered is his development of the three laws of planetary motion. As imperial mathematician, Kepler inherited all the data collected by Tycho Brahe over the previous 40-year period. Kepler, through grueling hours of analysis (over the course of years), deduced the motion of the planets and discovered that it fit most accurately with the Sun-centered model of the solar system put forward by Copernicus, albeit with the critical modification that the planetary orbits are not ideal circles but elliptical paths. Furthermore, Kepler's analysis of the planets' motion in time allowed him to state three geometrical laws that appeared to describe the motion of *all* planets. It was the crowning achievement of Newton's law of gravitation that it was able to re-create and derive Kepler's observational laws from first principles.

Galileo Galilei (1564–1642). Galileo was the son of a musician living near Pisa, Italy. At a young age, he sought to join a monastic order but was forced to return home by his father, who had already decided that his son was to become a medical doctor. Over the course of his medical studies, Galileo was exposed to mathematics and natural philosophy, which he took to immediately. He slacked off in his other classes, devoting all his energy to those two subjects. By the age of 21, he had earned an appointment as a teacher of mathematics in Siena. By 1592, he was offered an appointment as a professor of mathematics at the University of Padua.

Although much of Galileo's work was in the area of engineering (he more than doubled the magnification of telescopes of the time) and astronomy (it is for him that the Galilean moons of Jupiter are so named), the work for which he is most famous is the *Dialogue of Two Chief World Systems*, which he published in 1630. This was framed as a debate between the Copernican model of the heavens, which placed the Sun at the center and the other planets orbiting around it, and the Ptolemaic system, which placed the Earth at the center of the heavenly system. The confrontational manner in which he wrote this work earned Galileo censure by the Church.

Galileo is also perhaps the most famous figure associated with overturning the Aristotelian and Ptolemaic models of physics, in large measure because of his conflict with the Church. His work was extremely insightful, however, and inspired many future scientists, up to and including Einstein.

Isaac Newton (1643–1727). Newton is the father of physics, indeed, of all of modern science in many ways. I can think of few individuals of the last 1000 years with more direct and profound influence on the human condition. Isaac Newton's masterwork, the *Principia*, articulated not only a number of physical laws but also the scientific method itself. Newton's laws describe and (to some extent) explain motion and gravity. When faced with the need to solve the equations he developed, Newton *invented* the calculus required to solve them. His central laws are *universal*, applicable to any system in any circumstance. Even today, their accuracy and power is extraordinary. Although Newton's laws must be extended under extreme conditions (for example, for objects traveling near the speed of light), they still form the basis for much of modern technology. Newton was involved with both theory and experimentation, and his research touched on and formed the roots of many branches of modern physics, including optics, thermodynamics (heat), fluids, and more. Students in freshman physics learn about Newton's work in their first semester (then repeatedly, with further depth, as they progress). The metric unit of force, the *newton*, is named in his honor. Newton was not a pleasant or easy man. He had a big ego, never married, and had many disputes over intellectual priorities during his life. However, in an uncharacteristic but famous quote, he said, "If I have seen further, it is by standing on the shoulders of giants."

Henry Cavendish (1731–1810). Of all the 18th-century physicists, Cavendish was one of the most eccentric. He was pathologically shy—to the point of having a second staircase installed in his house so that he could avoid seeing his housekeeper. When invited to scientific salons (a fashionable dinner party featuring important figures in a field of literature or science), the only social event he would attend, people seeking his opinion were advised to enter the room, not look at him, and speak their questions to the opposite wall.

Because of his shyness, Cavendish rarely published, and later review of his work revealed that he had discovered many laws relating to properties of gases, chemistry, and electricity before others who were credited with their discovery. The published work for which Cavendish is best remembered (*Philosophical Transactions of the Royal Society of London*, 1798) was the extremely accurate and precise determination of the density of the Earth using an experiment designed by John Michell (who died before he could complete it). The experiment used a delicate torsional balance, as well as mirrors and optics, to measure the force between two large weights in the lab. The current results for the mass of the Earth deviate by only 1% from the results that Cavendish obtained more than 200 years ago. The result is now framed as the first measurement of the universal constant of nature (known as G), which appears in Newton's formula for the gravitational force between objects.

James Watt (1736–1819). Watt was born the son of a Scottish shipwright and was largely home-schooled by his mother. At the age of 17, he traveled to London to become an instrument maker and became the head of a small workshop at the University of Glasgow upon his return to Scotland. While at Glasgow, Watt became interested in steam engines (then in their earliest stages). After studying one that was in the possession of the university, he came up with a scheme to dramatically improve their efficiency, but the machining issues in creating a prototype, as well as finding funding for the effort, proved difficult, occupying Watt for nine years before he formed a partnership with Matthew Boulton.

Both Boulton and Watt made a fortune off the steam engines produced by their partnership. Watt is also given credit for inventing the steam locomotive in 1784. Although he was not a scientist by trade, it was Watt's inventions that drove an entire branch of scientific inquiry for the next 100. The improved efficiency of his new steam engine also opened the way for an industrial revolution powered by steam and coal, rather than by rivers and waterwheels.

Nicolas Sadi Carnot (1796–1832). Carnot grew up through the tumult of the French Revolution and the Napoleonic wars. He was home-schooled by his father in mathematics and science, as well as language and music. After studying at the École Polytechnique under such notables as Ampère and Poisson, Carnot enrolled in a two-year course in military engineering.

After leaving active duty in the military to attend more courses in Paris, Carnot began (in 1821) studying the mathematical theory of heat, which led to modern

thermodynamics. He was driven by the problem of designing more efficient steam engines. His name is now attached to the *Carnot engine*, an idealized device that mathematically proved the theory that ideal efficiency of a heat engine depended on the difference in temperature between the engine itself and the surrounding environment, not on the nature of the substance used in the engine.

Carnot died in 1832 at the age of 36, only a day after contracting cholera in an epidemic that swept Paris.

James Prescott Joule (1818–1889). The son of a wealthy brewer, Joule had an early scientific education (home-schooled for 16 years, then tutored by John Dalton of chemistry fame). Joule was active in running the family brewery until its sale in 1854, initially treating science as a hobby. When he began looking into replacing the brewery's steam engine with a new electrical engine, science began to occupy more of his life.

Initially ignored by the Royal Society of London as a provincial dabbler, between 1840 and 1850, Joule discovered the law that is named for him—showing the connections between mechanical energy and heat—and continually refined his experiments, improving the accuracy of the results (because the nature of his discovery demanded extremely precise measurements!).

Although there was a dispute with a German scientist, Julius Robert von Mayer, as to who was the first to determine the relationships among work, energy, and heat, the unit that modern scientists use for energy is named after Joule.

The Early Chemists (1750–1860)

Antoine Lavoisier (1743–1794). Lavoisier was a French nobleman whose contributions feature prominently in chemistry, biology, finance, and economics. He identified the element oxygen in 1779 and showed that respiration by living beings was essentially the very slow combustion of organic material inside the body. In 1783, he dethroned the phlogiston theory of combustion, the previous model by which chemical reactions were understood.

Lavoisier introduced the law of conservation of mass; that is, that in chemical reactions, matter is neither created nor destroyed but simply changes form. His *Elementary Treatise of Chemistry* is considered to be the first textbook of modern chemistry.

His accomplishments in science aside, Lavoisier was a prominent member of the French nobility and served as a tax collector. The French Revolution did not treat such people well, and in 1794, he was framed for treason and guillotined (he was exonerated by the French government a year and a half after his death).

John Dalton (1766–1844). John Dalton was born in Cumberfield, England, and educated by his father, a teacher at the Quaker school in the same town. At the age of 12, he assumed that post upon his father's retirement. Although his initial

foray into teaching was a disaster, he kept at it and passed the majority of his life earning a living as a teacher, either at a public post or as a private tutor.

In 1800, Dalton became the secretary of the Manchester Literary and Philosophical Society, through which he proposed the major work that he is remembered for. Inspired by Lavoisier's work, Dalton proposed his atomic theory, that is, that all matter is made of tiny, indivisible atoms. Everything about a certain atom can be known by knowing what element that atom is—all atoms of one element are identical but are fundamentally different from the atoms of each other element. Dalton's atoms can be neither created nor destroyed and are only moved about in chemical processes.

In 1837, Dalton suffered an attack of paralysis and again in 1838. In early 1844, he suffered a stroke, and his last meteorological observation is recorded the day before he was found dead by an attendant in July 1844.

Amedeo Avogadro (1776–1856). Born to a noble Italian family, Avogadro graduated with a law degree and began practice at the age of 20. Soon thereafter, he became interested in physics and mathematics and, in 1809, began teaching both subjects at the high school level. While he was teaching, he first proposed what is now known as Avogadro's law—that gases of equal temperature, pressure, and volume (no matter what the gas is) contain the same number of molecules. *Avogadro's number* is named in his honor and refers to the number of atoms contained in 1 mole of substance (roughly 602 septillion—602,200,000,000,000,000,000—a very large number!)

Relatively little is known about Avogadro's personal life. He was given a post at the University of Turin in 1820 as a professor of physics. Though he was restricted from teaching for a time because of his political support of Sardinian revolutionary movements, he ultimately taught there until 1853, with only a brief hiatus.

The Exploration of Electricity and Magnetism (1700–1900)

Benjamin Franklin (1706–1790). Franklin is probably one of the most well-known classical scientists, after Newton and Galileo. His fame, however, comes mostly from his nonscientific pursuits (publisher, ambassador, revolutionary). In 1748, 15 years after publishing the first *Poor Richard's Almanac*, Franklin retired from the printing business to pursue other opportunities, scientific experiments being chief among them.

Franklin's most famous work was in the field of electricity. Scientists before Franklin had identified two different types of "electrical fluid," the "vitreous" and "resinous." Franklin was one of the first to propose that there weren't two separate fluids but that both were simply different manifestations of the same fluid—a concept we know today as electric charge. His famous kite experiment (whether Franklin ever actually performed it is uncertain) was designed to prove that lightning was electrical in nature by flying a kite in a storm and showing

that it collected an electric charge. The practical application of this theory led Franklin to invent the grounding wire and the lightning rod. Franklin's writings were well received in Europe, and his fame as a scientist overseas played no small role in his becoming an ambassador to Europe for the colonies before and during the American Revolution.

Charles-Augustin de Coulomb (1736–1806). Charles Coulomb's father was a successful lawyer and administrator, while his mother came from a quite wealthy family. As a child, he was given the finest classical education, studying language, literature, and philosophy, in addition to more modern subjects, including mathematics, botany, chemistry, and astronomy.

Coulomb studied to be an engineer for the French army, becoming an expert in structural design, fortifications, and soil mechanics. While working as a military engineer, he wrote seven papers (between 1785 and 1791), in which he developed the theory of attraction between charges, describing both how the force decreased with distance and how positive and negative charges interacted. Though these were his most important works as far as posterity is concerned, Coulomb participated in more than 300 committees for the French Academy of Science and wrote 25 memoirs, in addition to collaborating with many other important French scientists of his era.

Coulomb survived the tumult of the French Revolution (including the dissolution of the Academy of Science and its re-creation as the French Institute) and spent the twilight years of his life as inspector general of public instruction, setting up schools across France.

Alessandro Volta (1745–1827). Volta grew up and was educated in Italy. He was a professor of physics in Lombardy for most of his life, primarily interested in the study of electricity. In honor of his contributions to science, he was given the title of count by Napoleon in 1810. It is for him that we name the unit of electrical potential energy (per unit charge), the *volt*.

Volta's most famous contribution to science was the development of the *voltaic pile*, a very early battery. Previously, electricity had been studied by building up charge on metal spheres (in the same way that scuffing your feet across the carpet on a dry day builds up static charge on you), then studying how it interacted with other charges. Volta's chemical battery allowed for a steady source of charge to be produced, making it possible to study charges in motion and at rest. Coulomb turned electric forces into testable laws in the same way that Newton and Cavendish had done for gravity. The voltaic pile paved the way for Oersted and Ampère to do the same for electrical currents, to find their connection to magnetism, and eventually, for Maxwell to fully unify the two forces.

Thomas Young (1773–1829). One of the contenders for the title "Last Man to Know Everything," Thomas Young's knowledge was broad and far reaching. He studied medicine and the optics of the human eye and was one of the first

scholars to translate the Rosetta Stone, which allowed us to read Egyptian hieroglyphs. He was born as the youngest of 10 children to a Quaker family in England and, by the age of 14, was said to be able to read 12 ancient languages!

For physicists, Young's most famous work was his double-slit experiment, in which he passed a beam of light through two narrow slits and observed a diffraction pattern on a screen on the other side. Even in modern physics, the results of this experiment are used as one of the strongest pieces of evidence in favor of the wave nature of light, though it would take until Maxwell's equations to demonstrate just what light is a wave of.

André-Marie Ampère (1775–1836). A French scientist and professor, Ampère was one of the first and most successful to expand on Oersted's connection between electric and magnetic forces. Ampère's name is now attached to the law describing the interaction of currents, reducing magnetism to the result of the motion of small charge carriers. Ampère's ultimate legacy to physics is overshadowed by that of Maxwell, but he was a pioneer in the study of electrodynamics, as Newton and Galileo were for mechanics (although he was not nearly so colorful a personality!). Although later scientists are given credit for more fully developing the theory, Ampère was one of the giants on whose shoulders they stood. Ampère spent the latter part of his career (after 1827) studying philosophy, which he considered "the only really important science."

Hans Christian Oersted (1777–1851). The name of this Danish physicist would likely be lost to obscurity were it not for happenstance. While preparing for a public lecture in 1820, Oersted noticed that a moving current caused a deviation of a nearby compass needle. After some intensive investigation, he published this discovery, which provided the impetus to other scientists (Ampère and Faraday foremost among them) to develop the mathematical and conceptual frameworks for understanding this phenomenon, culminating in the work of Maxwell.

Oersted's discovery would not have been so sensational except that it was in direct contradiction to the hypothesis of Coulomb, which had been taken as fact, that there categorically could be no interaction between electricity and magnetism. It took a direct repetition of the experiment, two months after the initial publication, in front of the French Academy for that body to accept the data as something other than blatant falsification.

Johann Carl Friedrich Gauss (1777–1855). Gauss's brilliance was revealed early: The story is that by the age of 7, he amazed his teachers by almost instantly summing all the numbers between 1 and 100 (by the trick of realizing that he could rearrange the numbers into 50 pairs that each added to 101 [$1 + 100$] + [$2 + 99$]...).

Gauss published works in both mathematics and practical astronomy, collecting observations used to further refine the known orbits of planets for 30 years. His mathematical work was concerned with differential geometry, inspired by an

early job in surveying. Perhaps his greatest contribution to physics, though, was his work on potential theory—an alternative means of representing forces felt by an object, or fields, resulting in the mathematics of Gauss’s law, the first of Maxwell’s equations (describing the relationship between an electric field and the charges that create it). Gauss’s other accomplishments included constructing a primitive telegraph and estimating the position of the magnetic south pole of the Earth. After his friend Wilhelm Weber was forced to leave the University of Göttingen (where Gauss himself taught), Gauss became less involved in active research, preferring to follow the developments of younger mathematicians.

Michael Faraday (1791–1867). Born the son of a blacksmith, Faraday was a self-educated bookbinder who was hired as a laboratory assistant of Humphrey Davy in 1812, with his sole recommendation being a complete set of notes on Davy’s own public lectures. Faraday’s humble upbringing put his early career at odds with the “gentlemen’s” society of early-19th-century physics, and his treatment at the hands of Davy (who blocked Faraday’s admission to the Royal Society for six years) and others almost caused him to leave science altogether.

Having learned physics with no formal training in mathematics, Faraday’s work was a model of tremendous mathematical intuition and incisive analogy, with relatively little formal mathematical development. This methodology put him at odds with the likes of Ampère and Maxwell, whose work focused on careful mathematical deliberation. Across a scientific career that spanned 40 years, Faraday is most well known for his development of the concept of the electromagnetic *field*, an intermediary in the interaction of two objects at a distance.

His work in the 1830s is one of the first conclusive discoveries of electromagnetic induction—the use of changing electric and magnetic fields to create currents—which he then harnessed to build the first dynamo, a device that converts mechanical energy into electrical current and vice versa and serves as the basis for modern electrical generators. Faraday is also credited with discovering the first connections between magnetism and light, which opened the way for Maxwell’s later (and most important) work.

James Clerk Maxwell (1831–1879). A Scotsman, born without privilege or high social rank, Maxwell worked in the fields of mathematical physics and electricity and magnetism during the 1800s, when the scientific community was tackling this “exotic” subject with great vigor. Maxwell was especially intrigued by the discoveries of Michael Faraday (himself a man of humble beginnings), who had introduced the concept of force field as a physically relevant entity. Maxwell succeeded in mathematically describing *all* phenomena of electric and magnetic origin in a set of four relatively simple equations, now called *Maxwell’s equations*. For the most part, these equations had been developed over the previous decades by others, but Maxwell organized and formalized them and added a key component, based not on experiment but his own aesthetic mathematical sense of symmetry, intimately and permanently unifying

electricity and magnetism. Maxwell discovered that these equations lead to the phenomenon of “traveling electromagnetic radiation,” moving at the speed of light, and with this, he realized the deep connection of electricity and magnetism to optics, as well.

Today, Maxwell’s equations and the corresponding unification of forces are regarded as one of the grand highlights of human intellectual achievement. They form the basis of electrical engineering and modern optics and have survived the discoveries of modern physics in the 20th century essentially unscathed. They paved the way for the discovery of relativity (being fully relativistic equations, even though Maxwell hadn’t appreciated that!) and form the classical underpinnings of quantum electrodynamics, the quantum theory of light. Studying Maxwell’s ideas generally forms the second half of any standard college-level introductory physics course.

Heinrich Hertz (1857–1894). Hertz studied under some of the finest minds in German universities and obtained his Ph.D. in physics by 1880, at the age of 23. He experimentally demonstrated the existence of electromagnetic waves, as predicted by Maxwell’s equations. He also discovered the photoelectric effect, though it would take Einstein to explain its origin. Hertz died at the age of 37 (of blood poisoning). Marconi followed up quickly on Hertz’s experiments as a means to send signals, with the invention of the radio.

William Thomson, Lord Kelvin (1824–1907). William Thomson is, in many ways, the bridge between Faraday’s intuitive brilliance and Maxwell’s ultimate formulation of electrodynamics. Raised by his father, a widowed professor of mathematics, William was precocious in his scientific exploits. By the age of 15, he had already won a prize for an “Essay on the Figure of the Earth,” and he began publishing papers (under a pseudonym) by age 16. By the time he was 22, he had earned a position as the chair of natural philosophy at the University of Glasgow, a position he held for 53 years. In 1845, Thomson began corresponding with Faraday, and the two men established a relationship of mutual respect. What Faraday approached intuitively, Thomson approached with mathematical models, including the mathematics developed by his lifelong friend George Stokes in studying heat flow.

Thomson’s correspondence with James Maxwell led to the latter’s tackling the problem of mathematically expressing Faraday’s “lines of force,” an effort that culminated in what we now call Maxwell’s equations.

Bibliography

Essential Reading:

Hewitt, Paul. *Conceptual Physics*. Reading, MA: Addison Wesley, 2005. This is a textbook for a course perhaps a little more technically oriented than ours, but it's really wonderful. Hewitt is very accessible, with a strong focus on sense-making and understanding. Highly recommended to go along with this course if you want to push a little farther. Be aware: Trying to "read" a textbook like this one is a difficult task. You can't read it like a work of literature (much less like the daily paper or a novel)—it requires time for calculations, projects, and reflection.

Hobson, Art. *Physics: Concepts and Connections*. Englewood Cliffs, NJ: Prentice Hall, 2003. This is a textbook for a traditional course very much like ours. Aimed at the nonscientist (no algebra, minimal use of graphs and numbers), it's a good survey of the field. Hobson follows four themes: how we know science, post-Newtonian physics (which is not an emphasis of this course!), energy, and the social context of physics. Hobson also follows a quasi-historical path, with quite a bit of discussion about the nature of science and the context and significance of the big ideas in physics.

March, Robert H. *Physics for Poets*. New York: McGraw-Hill, 1996. This book is very much on the level and style of our course. This one is not a conventional physics text at all; it has a few equations but doesn't fuss with their manipulation. It is much more a historical overview of the big ideas and central characters of physics. A good companion to this course, although a bit brief if you become interested in any given individual and, indeed, a little superficial (focusing on the "ideal physicists" rather than troubling itself with historical complexities) if you have a historical bent, but a good start for getting into this material.

Pollock, Steven, and Ephraim Fischbach, *Thinkwell Physics I* (www.thinkwell.com). This is a multimedia video textbook, a collection of 10-minute "mini-lectures" by yours truly, covering much of classical mechanics, plus waves and oscillations. These lectures are designed to go along with a much more traditional physics course, but if you concentrate on the introductory lectures in each topic (rather than on the ones focused on calculating and problem-solving), they should complement the material in this course nicely. And if you decide you do want to delve a little farther into the mathematics on your own, *Thinkwell* will certainly be a useful guide.

Recommended Reading (referenced explicitly in this course):

Crease, Robert. *The Prism and the Pendulum*. New York: Random House, 2003. A lovely book, aimed very much at the audience for this course. His theme is that science and scientific experiments can be beautiful—not in some abstract way, not stretching the definition of the word, but meaning precisely what we always mean by *beauty*. Science and scientific experiments convey

harmony, symmetry, and depth; they lead us to realizations about ourselves and the world; they change our outlook in positive ways; and they make us happy. Crease has picked 10 great experiments and explains them clearly and compellingly. Although the last few reach the realm of modern physics, this book is a nice complement to this course.

Cropper, William. *Great Physicists: The Life and Times of Leading Physicists from Galileo to Hawking*. New York: Oxford University Press, 2001. Short chapters on about 30 of the most influential physicists from Galileo to Hawking, with details on both the people and the physics they discovered. There are some equations, though the math is not a heavy emphasis, and they are often treated separately from the conceptual and historical discussions. Brief by its nature but well written and a nice mix of culture, significance, and physics itself. I learned a lot from this book!

Feynman, Richard P., Robert B. Leighton, and Matthew Sands. *The Feynman Lectures on Physics*. Reading, MA: Addison Wesley, 2005. I have to include this textbook, although “reading” it is essentially an impossible task for someone not already familiar with the basics of physics. Feynman sat down with the goal of presenting the great fundamental ideas of physics at an introductory college level; the result is this compilation of notes/text for his extraordinary freshman physics course at CalTech in the 1960s. He reformulated the traditional “canon” based on his own ingenious insights, creativity, and novel point of view. Once you’ve got some solid understanding of the basics of physics (even somewhat beyond where this course will take you), going back to this text will be a pleasure and a reward.

Gleick, James. *Isaac Newton*. New York: Vintage Books, 2004. An engaging biography of Newton that discusses the physics only qualitatively but sets a clear background of the context and culture in which Newton worked and the significance of his work. Detailed and full of insight into Newton’s personality, this book paints a more complete picture than most biographies.

Gonick, Larry, and Art Huffman. *The Cartoon Guide to Physics*. London: Collins, 2005. I know that these *Cartoon Guides* may look superficial, but I’m a fan of this series. The coverage is solid, and the books are clever and fun to read. This book matches well with our course, and there’s a nice mix of representations—I believe the cartoons do help make sense of the basic ideas of classical physics.

Lightman, Alan. *Great Ideas in Physics*. New York: McGraw-Hill, 2000. Lightman zooms in on only four “great ideas” (two from classical physics, energy conservation and the second law of thermodynamics). His perspective melds physics, philosophy, and art, although he focuses on the physics, walking you through a little bit of the mathematics to get a taste for the role of math in understanding. A little limited in scope, but useful if you would like to begin the trip from conceptual physics to mathematical physics without taxing your math skills (you need to be comfortable with ratios and basic algebra). The questions for reflection at the end of the book are particularly good.

Further Recommended Reading:

Asimov, Isaac. *The History of Physics*. New York: Walker & Co., 1984.

Asimov has produced a readable, comprehensive history of physics, although it's not so much history as it is details and concepts mixed in with history, biography, and philosophy of science.

Christianson, Gale. *Isaac Newton* (Lives and Legacies Series). New York: Oxford University Press, 2005. A brief, simple introduction to Newton and his physics. Although it's a little less nuanced than Gleick's biography (listed above), I nevertheless enjoyed this selection.

Cohen, I. Bernard. *The Birth of a New Physics*, rev. ed. New York: W.W. Norton, 1991. Good historical coverage of the physics of the early scientific revolution, particularly in the 16th and 17th centuries.

de Campos Valadares, E. *Physics, Fun, and Beyond: Electrifying Projects and Inventions from Recycled and Low-Cost Materials*. Englewood Cliffs, NJ: Prentice Hall, 2006. This is a collection of simple, "at-home" experiments and projects, spanning much of classical experimental physics, suitable for science fair ideas, family projects and gifts, teaching/outreach, or just plain interesting hobby activities. Great for those who prefer to learn by doing, although the author also takes care to explain the physics behind each of the projects.

Ehrlich, Robert. *Turning the World Inside Out and 174 Other Simple Physics Demonstrations*. Princeton, NJ: Princeton University Press, 1990. Another collection of physics activities and demonstrations, this one is aimed a little more at a teacher, but it provides inspiring ideas for anyone interested in watching physics in action in clear, simplified ways. Each project has detailed construction instructions and physics explanations, and almost all the projects are quite simple, requiring relatively little in the way of expense or equipment.

Epstein, Lewis. *Thinking Physics: Understandable Practical Reality*. San Francisco: Insight Press, 2002. A wonderful collection of cartoon-based "thinker" puzzles, designed to see if you have a strong conceptual understanding of many of the topics of classical physics, such as how tides work or why steel ships float. These questions are often designed at the level of an introductory college course (some of them involve sense-making of the mathematics in a traditional physics class), but by and large, there is no calculation of any kind required for these questions, just clear thinking about the underlying principles of physics. Epstein is great at talking through the wrong answers to help you "think about your own thinking."

Ferguson, Kitty. *Tycho and Kepler: The Unlikely Partnership That Forever Changed Our Understanding of the Heavens*. New York: Walker & Co., 2002. A good biography of these two remarkable historical figures that includes some of the essential physical ideas, highlighting the brilliance of Kepler's achievements.

Feynman, Richard. *The Pleasure of Finding Things Out*. New York: Basic Books, 2005.

———. *Six Easy Pieces: Essential Physics Explained by Its Most Brilliant Teacher*. New York: Basic Books, 2005.

———. *The Character of Physics Law*. New York: Modern Library, 1994.

———. *The Meaning of It All*. New York: Basic Books, 1998.

Richard Feynman is one of the great 20th-century physicists, and his perspectives on the nature of science are unparalleled. *The Pleasure of Finding Things Out* is a collection of Feynman's essays on a number of topics, offering nontechnical but delightful insights into how science is done. *Six Easy Pieces* is a collection of the least technical chapters from the *Feynman Lectures*, in which he introduces big topics of (mostly, with one or two exceptions) classical physics ideas. *The Character of Physical Law* is in a similar style, focusing on some central topics of physics and talking both about the details and the "meta" issues, the nature and consequences of science. *The Meaning of It All* drifts farther from the physics and into issues of the connections among science, religion, and politics. There are many other books by (and about) Feynman, all of which are highly recommended, although some go beyond the "classical" focus of our course.

Gamow, George. *The Great Physicists, from Galileo to Einstein*. New York: Dover Publications, 1988. George Gamow, inventor of the Big Bang theory, is a skilled author for non-physicists. Gamow's books are gems, inspiring, and suitable even for young adults. This "biography" of physics covers much of the classical physics topics we've focused on, ending with some discussion of modern ideas.

Gribbin, John. *The Scientists: A History of Science Told through the Lives of Its Greatest Inventors*. New York: Random House, 2004. Five hundred years of science in 672 pages—this is a comprehensive book, written compellingly, with anecdotes and stories. Gribbin organizes and connects the characters and developments. A reference (you can wander from spot to spot in the book if you want) that also makes for a compelling read, albeit a little heavy going.

Heilbron, John L. *The Oxford Guide to the History of Physics and Astronomy*. New York: Oxford University Press, 2005. An encyclopedic collection (quite literally) of information about the personalities and the physics; very complete, informative, and surprisingly interesting just to read.

Holton, Gerald, and Stephen Brush. *Physics, the Human Adventure: From Copernicus to Einstein and Beyond*. New Brunswick, NJ: Rutgers University Press, 2001. Teaching physics with an accurate historical and philosophical perspective, with more history than March's *Physics for Poets*.

Jargodzki, C., and F. Potter. *Mad About Physics: Braintwisters, Paradoxes, and Curiosities*. New York: Wiley, 2001. Another collection of physics puzzles; maybe just a little less "physics-serious" than Walker's *Flying Circus* (see below), it provides briefer explanations to a broader assortment of puzzles. This entertaining book takes advantage of paradoxes as a teaching tool and includes wonderful quotes.

Jungnickel, Christa, and Russell McCormmach. *Intellectual Mastery of Nature: Theoretical Physics from Ohm to Einstein*, 2 vols. Chicago: University of Chicago Press, 1990. This book focuses on the emergence of theoretical physics as a discipline, mostly in Germany and Austria, between 1850 and 1925, offering a largely biographical development and context. A scholarly work; again, a little heavy going but particularly appropriate for the electricity and magnetism section of this course.

Kakalos, James. *The Physics of Superheroes*. New York: Gotham, 2005. I may have a soft spot for whimsical physical texts, but this one strikes me as very successful at teaching the basic principles of classical physics in the context of comic-book superheroes. The comics provide a framing for Kakalos to teach the basic principles of physics in an engaging way.

Kuhn, Thomas. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press, 1996. Kuhn is a philosopher of science who popularized the notion of paradigm shifts. This book discusses the nature of the evolution and progress of scientific ideas. Kuhn argues that, for the most part, scientific progress is incremental and exists within a scientific (and sociological) framework; only rarely are "revolutions" possible. Some traditional physicists disagree with Kuhn's arguments regarding the extent to which scientific progress is socially constructed, but the work is interesting, challenging, and influential.

MacAulay, David. *The New Way Things Work*. Boston, MA: Houghton Mifflin, 1998. A cartoon-based book, whimsical and amusing, it takes an engineering and physics approach to examine devices and ask how they work, incorporating physics concepts in a meaningful way. Aimed at children, but child-like adults (like me) can appreciate this book.

Mahon, Basil. *The Man Who Changed Everything: The Life of James Clerk Maxwell*. New York: John Wiley & Sons, 2004. A brief and readable biography of Maxwell's life and science. It doesn't get so much into the physics but offers good insights into Maxwell as a human being and scientist!

Nye, Mary Jo. *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940*. Cambridge, MA: Harvard University Press, 1999. A thorough study of the two sciences together, emphasizing the social and historical context.

Purinton, R. D. *Physics in the Nineteenth Century*. New Brunswick, NJ: Rutgers University Press, 1997. A little heavy going, this is pure historical analysis but covers all the major players in the physics of the 1800s, with an emphasis on the development of ideas leading to the coming revolutions of the 20th century.

Shamos, Morris, ed. *Great Experiments in Physics: Firsthand Accounts from Galileo to Einstein*. New York: Dover Publications, 1987. A collection of 25 key experiments (including many discussed in this course), introduced and

explained, then followed with annotated original works. A unique book; it's great (and surprisingly rare) to read the originals.

Spielberg, N., and B. Anderson. *Seven Ideas That Shook the Universe*. New York: Wiley, 1995. A comprehensive text, covering the ideas of this course and following a conceptual framework. Aimed at the non-physicist. A highly readable text.

Vollmann, William. *Uncentering the Earth: Copernicus and the Revolutions of the Heavenly Spheres*. New York: W.W. Norton, 2006. A book (written by a nonscientist) that explores how Copernicus could have come up with the heliocentric hypothesis and convinced himself of its correctness. Not always the easiest read but a fascinating story that gets at the core of the start of the scientific revolution and the nature of scientific reasoning.

Von Baeyer, Hans Christian. *Warmth Disperses and Time Passes: The History of Heat*. New York: Modern Library, 1999. A well-written historical and physical treatment of thermodynamics. A good introduction to the story of thermodynamics, which alas, we barely have time to even introduce in this course.

Walker, Jearl. *The Flying Circus of Physics with Answers*. New York: Wiley, 1977. A collection of "puzzles," all curious, real-world phenomena for you to think about, that demand physical explanation: Why does chalk squeak? How does a one-way mirror work? What's the "green flash" at sunset? Why wasn't Ben Franklin killed when he flew his kite in a lightning storm? These questions are a lot of fun to explore! The puzzles are organized around broad themes of classical physics (such as mechanics, optics, acoustics, thermodynamics, and so on).

Standard Introductory Physics Textbooks (a selection):

A number of textbooks are used in introductory college-level physics courses. These are not generally designed as "standalone" reading but are meant to be used with the guidance and support of an instructor. If you decide to buy one to try out on your own, be advised that these are not "evening reading material." There are so many, I list below only a few of my personal favorites (the one I authored, *Thinkwell Physics*, was listed with the essential texts, above). Many others are in use in college courses around the world; this is a very abbreviated list!

Bloomfield, Louis. *How Things Work: The Physics of Everyday Life*. New York: Wiley, 2005. An unconventional introduction to physics, aimed at nonscientists who want to learn the basic principles of physics and the applications to everyday life. Rather than organizing the text around physics concepts, the author focuses each chapter on a technological or physical application (generally both common and interesting!). This approach develops the physical principles in a deeply motivating way. Of all the texts listed in this section, Bloomfield's is likely to be the most accessible to the interested

layperson, but even so, it remains a textbook that would probably best be used in the framework of a course with an instructor.

Chabay, Ruth, and Bruce Sherwood. *Matter and Interactions*. New York: Wiley, 2003. Most of the standard introductory texts follow pretty much the same pattern, teaching the same classical physics topics in roughly the same order (perhaps adding modern physics in the end) and focusing on the same mathematical skills. This text offers a fresh approach. Sherwood and Chabay are part of the physics education research community and treat introductory physics from a completely modern perspective. Relativity and the atomic model are involved right from the start, and the separation between classical and modern physics is purposefully blurred. The authors emphasize modeling systems throughout. If you want to learn physics with the intent of becoming a physicist, this would be an excellent first textbook to use, but again, the level of mathematics and sophistication required is fairly high; this is certainly not “light reading.”

Giancoli, Douglas. *Principles with Applications*. Englewood Cliffs, NJ: Prentice Hall, 2004. This is a fairly traditional and popular introductory textbook, designed specifically for an algebra-based course. Many of the applications and examples in the book are tailored to students who are less likely to be physicists or engineers but might be interested in medicine, biology, or architecture.

Halliday, David, Robert Resnick, and Jearl Walker, *Fundamentals of Physics* (New York: Wiley, 2004), or perhaps, Karen Cummings, Priscilla Laws, Edward Redish, and Patrick Cooney, *Understanding Physics* (New York: Wiley, 2004). Halliday, et al., has been one of the standard texts at many schools for many years. As you move up to more recent editions, there is a stronger focus on conceptual understanding. The *Understanding Physics* book is basically a new, updated version, redesigned to incorporate physics education research results, but it is nevertheless still a dense, heavy, mathematically centered introductory text. It remains one of my favorites for teaching calculus-based physics and engineering courses.

Knight, Randall. *Physics for Scientists and Engineers: A Strategic Approach*. Reading, MA: Pearson/Addison-Wesley, 2003. Similar in content to Halliday, Resnick, and Walker, above. Knight has also taken a stab at rewriting the conventional introductory calculus-based textbook with physics education research results in mind. That means using research on common student learning difficulties, incorporating alternative representations and metaphors, and including problems and questions designed through iterative research studies.

Moore, Thomas. *Six Ideas That Shaped Physics*. New York: McGraw-Hill, 2003. This is another modern, nonstandard approach to the introductory text. Breaking the subject into six fundamental “big ideas” (such as conservation laws, reference frame-independence of physics, universal laws, and so on), Moore leads the student to apply basic principles to solve realistic physical

problems, rather than following a more traditional, plug-'n-chug, formula-centric approach.

Internet Resources:

The Web has an overwhelming supply of resources regarding introductory physics (*some* of which are even accurate and useful)! The task of selecting just a few sites is difficult (and the situation will likely evolve so quickly as to limit the usefulness of this list), but below are a few Web sites that I believe are definitely worth investigating.

<http://phet.colorado.edu>. This is the simulation site referred to throughout this course, developed by the Physics Education Research group at the University of Colorado.

<http://natsim.net/en.html>. This site contains links to other physics simulation collections. Although the phet sims (listed above) are very helpful, they cover only a narrow range of topics. This page will take you to sites with hundreds of applets. In addition, you might want to visit sites mentioned explicitly in the lecture notes:

- www.cecm.sfu.ca/~scharein/astro
- www.walter-fendt.de/ph11e
- <http://physics.bu.edu/~duffy/semester1>

<http://howthingswork.virginia.edu/>. Louis Bloomfield (whose introductory textbook for nonscientists, *How Things Work*, is also on my recommended list) has created a high-quality frequently-asked-questions page for explanations about the physics of everyday life. If you have a question about a device or phenomenon, there's a pretty good chance you will be able to find an answer on this page.

<http://www.merlot.org/merlot/materials.htm?category=2737>. The Merlot Web site (www.merlot.org) is a national resource for academics in a variety of fields to compile learning materials. The link above takes you specifically to a collection of peer-reviewed resources for classical mechanics. (Moving up a level will allow you to explore more of physics, including electricity and magnetism and modern physics)

www.aip.org/history/syllabi/books.htm. The AIP is the American Institute of Physics. This is the institute's "bibliography" page, with many highly recommended books. (Some of them I have listed above, but I've tried to keep my bibliography distinct. AIP's selection is very good!)

www.aip.org/history/gap/. Another AIP page, this one has links to the works of some great American physicists (including original papers, with explanations), including Franklin, Gibbs, and many others.

www.physlink.com/Education/History.cfm. A collection of links to other sites, with history and timelines. Also many links to science museums.

www-gap.dcs.st-and.ac.uk/~history/index.html. This page calls itself the History of Mathematics Archives, but it's very thorough, and its compilers apparently

consider most physicists to be mathematicians. The biographies are interesting and comprehensive without being overwhelming. This is my favorite site for a “quick read” about some historical figure I’m interested in.

www.upscale.utoronto.ca/PVB/PVB.html. This is the University of Toronto’s *Physics Virtual Bookshelf*. The staff at the university has put together an impressive collection of links and articles. A nice place to start digging deeper into the history and content of physics.

<http://en.wikipedia.org/wiki/Physics>. Wikipedia is a collective, informal, Web-based encyclopedia. This site is frequently helpful, and I use it all the time (not just for physics!). But beware: It is the nature of Wikipedia that there can, on occasion, be mistakes or even sheer nonsense here. These articles are submitted by individuals without “authorization”; this is not the usual method of scientific peer review by any stretch of the imagination. If you learn something here, follow up to make sure that it’s accurate and reliable. Nevertheless, Wikipedia is often my first stop when I’m looking up something new.

www.physics.org/. From the Institute of Physics, many links and interactive sites for history and the “physics of everyday life.”

<http://physicsweb.org/bestof/history>. Another compilation of historical information and links, this one put together by the Institute of Physics (IoP).

www.hssonline.org/teach_res/essays/mf_essays.html. A recommended bibliography from the History of Science Society. Once again, many good books here, organized in a variety of categories (social, historical, bibliographic). An excellent resource for delving further into the history of classical physics!

<http://galileo.rice.edu/>. A comprehensive Web site about Galileo.

www.tychobrahe.com/eng_tychobrahe/index.html. A comprehensive Web site about Brahe.

www.clerkmaxwellfoundation.org/. A comprehensive Web site about Maxwell.

Notes





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